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Productivity and Sustainability of *Acacia* Plantations in Vietnam

By

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Declaration of Originality

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Trieu Thai Hung contributed 70% (conducted all experimental work, analysed data, wrote the initial manuscript). Auro Almeida, Alieta Eyles and Caroline Mohammed (30%) guided experimental design, advised on statistical analysis, revised and edited the manuscript.

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2. Thuyet, D.V., Do, T.V., Sato, T., **Hung, T.T**., 2014. Effects of species and shelterbelt structure on wind speed reduction in shelter. Agroforestry Systems 88, 237 – 244. http://dx.doi.org/10.1007/s10457-013-9671-4.

ABSTRACT

Clonal *Acacia* hybrid (*A. mangium* × *A. auriculiformis*) is widely planted across Vietnam due to its fast growth and adaptation to a wide range of site conditions. But there is significant variability in *Acacia* hybrid plantation productivity across Vietnam, most likely explained by marked regional differences in soils, climate and management practices. There is insufficient knowledge to allow the matching of management practices to site potential. While the environmental benefits of *Acacia* hybrid plantations can be assumed to be similar to other tree plantings, there is a paucity of specific knowledge about the impact of *Acacia* hybrid plantations as a land use in Vietnam. My research used empirical mensuration and modelling approaches to broaden the knowledge of *Acacia* hybrid's response to its environment and its impact on this environment. Three studies were undertaken (1) an estimation of *Acacia* hybrid productivity for a range of climate and soils, (2) an examination of the impact of alternative silvicultural management practices on sawlog production from *Acacia* hybrid plantations (3) an investigation of the impact of *Acacia* hybrid plantations on soil properties in comparison to fallow land within a shifting cultivation system.

For the first study we calibrated the 3-PG growth model using ten permanent sample plots located in stands aged 1, 3 and 6 years. The model was then validated using 55 additional permanent plots from 12 plantations growing in four regions of Vietnam that support plantation forestry. The model performed well for most of the validation sites; model efficiencies (*EF*) were ⩾0.76. The model was more accurate in predicting the productivity of plantations in the North and North Central Coast than in the South and South Central Coast regions. Growth was most affected by soil water

deficit in this wet/dry tropical environment, than by temperature, particularly in the north. Soil fertility was best predicted by a relationship with soil organic carbon and the base cations Ca^{2+} and K^{+}. Across regions, the mean current monthly increment of stand volume for a 15-yr rotation was 3.21 and 1.97 m^3 ha^{-1} $month^{-1}$ for the wet and dry seasons, respectively. Sensitivity analysis indicated how much the model parameters affect the main outputs and how this changes with stand age.

In the second study the growth responses of *Acacia* hybrid plantations to a range of thinning and fertiliser-at-thinning treatments at six experimental trials in North, South Central Coast and South Vietnam were quantified using empirical data and compared to predictive data derived from the 3-PG process-based model. Different experimental thinning regimes reducing initial stockings of 2000, 1667 and 1111 trees ha^{-1} to 1333, 1000, 900, 667, 600 or 450 trees ha^{-1} at ages varying from 2 to 5.6 years were applied. Tree diameter (*DBH*) responses to thinning and stand volume (*SV*) after thinning were greater in south than in North and South Central Coast Vietnam. Application of fertiliser at thinning increased *DBH* and *SV*, compared with the non-fertiliser control. Early thinning to 450 or 600 trees ha^{-1} resulted in the greatest *DBH* for all diameter classes and was the most successful treatment for sawlog production compared to other thinning regimes, with a substantial increase of sawlog volume and the proportion of larger diameter logs. Lighter thinning to 900 or 1000 trees ha^{-1} resulted in comparatively low diameter increments but higher yields of small sawlogs and total *SV* than higher intensity thinnings. The 3-PG process-based model was more accurate in predicting *DBH* and *SV* for all silvicultural treatments at sites in North and South Central Coast Vietnam than in the South where productivity was highest. Predictions suggested that extending the rotation length to at least 5 – 7 years in the

South and South Central Coast and 6 – 10 years in North Vietnam in *Acacia* hybrid plantations managed for large sawlog production would best optimise the production of this category of sawlogs and thus benefit growers.

There have only been a few studies that have examined the effect of land use on soil properties including total soil carbon (TC), total soil nitrogen (TN) and soil pH in Vietnam. Soil properties under tropical *Acacia* hybrid plantations (AH) and fallow land within a shifting cultivation system (FSC) were compared. We investigated various soil properties for the two land uses including TC, TN, pH, bulk densities and particle-size distribution in 10 cm increments down to 30 cm for 25 paired sites in northern Vietnam. The results show that TN and TC concentrations in AH were significantly higher at all 10 cm depth increments when compared to FSC. While both TC and TN decreased significantly with depth under both land uses, the C/N ratio only decreased in AH and not the FSC. However, there was a significant decrease in soil pH in AH at all depths (>0.4 pH units) and this may potentially cause acid infertility issues.

In summary, I parameterised, calibrated and validated the 3-PG process-based model for *Acacia* hybrid. The model provided an accurate description of the potential productivity of *Acacia* hybrid plantations across a wide range of climates and soils in Vietnam. *Acacia* hybrid plantations appear to improve TC and TN more than fallow land within a shifting cultivation system and thus have a demonstrated and positive impact on environmental sustainability. The 3-PG model can be used to predict stand growth of *Acacia* hybrid plantations managed for sawlogs, under different silvicultural regimes, with acceptable accuracy and could be a useful tool for strategic planning of thinning and fertilization. Overall, my thesis provides valuable information to enable sustainable forest management of *Acacia* hybrid plantations across Vietnam, the determination of potential productivity and the selection of those management practices which will optimise sawlog production.

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LIST OF ABBREVIATIONS AND SYNONYMS

3-PG	Physiological Principles Predicting Growth
ACIAR	Australian Centre for International Agricultural Research
AGROINFOR	Information Centre for Agriculture and Rural Development
AH	*Acacia* hybrid
Alt.	Altitude
APAR	Absorbed photosynthetically active radiation
ASW	Available soil water
avail. P	Available P
BA	Basal area
BD	Bulk density
CEC	Cation exchange capacity
CMI	Current monthly increment
C/N	Carbon:nitrogen ratio
Ca^{2+}	Exchangeable calcium
dbh	Diameter at breast height (1.3 metres)
DBH	Stand mean diameter
EF	Model efficiency
FR	Fertility rate
FSC	Fallow land within a shifting cultivation system
g_s	Stomatal conductance
H	Total tree height
K^+	Exchangeable potassium
LAI	Leaf area index

LAI 2000	Plant canopy analyser, Li-Cor, Lincoln, NE
Lat.	Latitude
Long.	Longitude
LSL	Large sawlog
MAI	Mean annual increment
MARD	Ministry of Agriculture and Rural Development of Vietnam
Mg^{2+}	Exchangeable magnesium
Na^{+}	Exchangeable sodium
PBM	Process-based model
PBMs	Process-based models
PW	Pulpwood
R^2	Coefficient of determination
RMSE	Root mean squared error
SA	Sensitivity analysis
SD	Standard deviation
SE	Standard error
SE Asia	South-East Asia
SLA	Specific leaf area
SOM	Soil organic matter
SOC	Soil organic carbon
SSL	Small sawlog
SV	Stand volume
TC	Total soil carbon
TN	Total soil nitrogen
Temp.	Mean monthly temperature

T_{max}	Mean monthly maximum temperature
T_{min}	Mean monthly minimum temperature
TW_{AGB}	Total stand above-ground biomass
V	Individual tree volume
VPD	Vapour pressure deficit
W_{stem}	Oven-dry weight of stem biomass (stem wood + bark + branches)
W_{foliar}	Oven-dry weight of foliage biomass
W_{root}	Oven-dry weight of root biomass
WUE	Water-use efficiency

CHAPTER 1

GENERAL INTRODUCTION

CHAPTER 1. GENERAL INTRODUCTION

1.1. Background and problem statement

Deforestation, forest degradation and the role of plantation forestry

Globally, deforestation in the period between 1990 and 2015 was estimated to be around 130 Mha with most forest loss occurring in the tropics and subtropics (FAO, 2015). The net annual rate of forest loss was highest in the early 1990s (0.18%) but dropped in the period 2010 – 2015 (0.08%) (FAO, 2015). Deforestation and unsustainable land use have created large expanses of degraded land in several countries in the Asia-Pacific region (Lamb, 2011). This loss of forest cover has led to a decline in subtropical and tropical forest ecosystems features, such as biodiversity, carbon sequestration and watershed protection, as well as a loss of goods, such as timber, originally provided by natural forests (Lamb et al., 2005; Lamb, 2011). Unsustainable logging practices in the past and an increased environmental awareness of the need to expand areas of conservation and rehabilitation have rapidly diminished the availability of native forests as sawlog resources in the tropical and subtropical regions (Lamb, 2011). To ensure their sustainable management for a range of values, forest managers need to know more about the environmental and ecological impacts of silvicultural practices in the short and long term.

Coinciding with reduced access to native forests for logging, rates of forest plantation establishment worldwide have been increasing from 4.1% to 7.0% of total forest area from 2000 to 2015, being equivalent to 277.9 Mha in 2015 (FAO, 2015). The largest areas of planted forest in 2015 were in East Asia (91.8 Mha) and Europe (70.4

Mha), followed by North America (42.1 Mha) and Southern and Southeast Asia (29.9 Mha) while the Caribbean (0.7 Mha) and Central America (0.4 Mha) had the smallest areas of planted forests (Payn et al., 2015). The area of planted forests in SE Asia was estimated to be 25.6 Mha in 2015, accounting for 8.7% of the total forest area including natural forest (FAO, 2015). In SE Asia, planted forests, comprising mostly of acacia, eucalypts and pine have been the primary source of feedstock for the pulp and paper industries (Harwood and Nambiar, 2014a), partly in response to the declining availability of industrial wood from natural forests. Together, areas of acacia and eucalypt showed an increasing trend and estimated at about 7 Mha in 2014 (Nambiar and Harwood, 2014). These planted forest areas provide substantial opportunities to increase hardwood production in the future.

In SE Asia, *Acacia* plantations can make an important contribution to boosting rural economic development by providing a supplementary source of long-term income from agro-forestry systems (Harwood and Nambiar, 2014a). The expansion of plantations in SE Asia requires not only an understanding of biophysical and climate factors but also the related socio-economic and environmental impacts (Harwood and Nambiar, 2014a). For example, in Vietnam, a significant part of plantation forestry is managed by many smallholders, accounting for 46% of the total area of plantation forests (Blyth and Hoang, 2013). Therefore, as forest products are likely to remain a valuable source of income for rural communities and important contributors to poverty alleviation, smallholders will require assistance in enhancing plantation productivity and being able to objectively compare potential returns from plantations with other land uses (Sang, 2008).

Plantations grown for roundwood

Roundwood can be used for industrial purposes, either in its round form (e.g. as transmission poles or piling) or as raw material to be processed into industrial products such as sawn wood, panel products or pulp. According to Indufor (2012), the total area of industrial roundwood forest plantation in the world was 54.3 Mha producing 770 M m^3 in 2012 and was projected to increase to 91 Mha by 2050. In 2012, 46.3% (~1.7 billion m^3) of the world's industrial roundwood from all types of forests, including natural forests and trees outside forests was sourced from intensively managed planted forests, particularly in the tropics and subtropics where 65% of production was from planted forests (Payn et al., 2015).

The greatest production of industrial roundwood in plantations in 2012 was in South America (193 M m^3), followed by Asia (151 M m^3) and North and Central America (104 M m^3) (Jürgensen et al., 2014; Payn et al., 2015). Increased demand for wood supply from planted forests is expected, while decreased production from planted forests is projected especially in dry forest regions such as USA or Africa (Payn et al., 2015). Thus, intensification of management and increasing productivity in existing forest land is required (Harwood and Nambiar, 2014a; Payn et al., 2015). Sarshar (2012) indicated that the greatest potential for high-yielding hardwood roundwood plantation development is centred in tropical regions, including SE Asia and parts of Africa and Central and South America, which offer attractive growing conditions.

Plantations grown for ecosystem services

In addition to providing large-scale wood supplies, the global forest area designated for carbon storage has increased from 1.3% in 1990 to 5.3% in 2015 (Miura et al., 2015). According to Federici et al. (2015), the global net source of CO_2 emissions from deforestation has decreased rapidly from 4.0 Gt CO_2 yr^{-1} to 2.9 Gt CO_2 yr^{-1} during the period 2001 – 2015. In contrast, the CO_2 emissions from forest degradation (the main cause of which is the selective logging of commercially valuable trees) have increased significantly from 0.4 Gt CO_2 yr^{-1} to 1.0 Gt CO_2 yr^{-1} in 1990 – 2015. Tropical forest plantations with their fast growing species play an important role in the global carbon cycle because they constitute a potential sink that can mitigate the effects of deforestation and degradation (Alemu, 2014). Mitigation of climate change through new afforestation of degraded lands may be achieved by either decreasing net carbon stock losses or increasing of average carbon stocks in the long term (Federici et al., 2015). If carbon is not captured and conserved in the long term, the sustainability of the plantation estate with respect to carbon conservation may be compromised (Phuong, 2011).

Management of plantations in subtropical and tropical environments

In temperate regions of the world, plantation forests have been historically managed over long rotations (e.g. >25 years) (Harwood and Nambiar, 2014b). In contrast, most plantations in subtropical and tropical environments are managed as short-rotation monocultures based on 5 – 10 years growth cycles although there are some plantations of teak in Java and India, and hybrid pine in Queensland, Australia that are managed in long rotation cycles typically of >25 years (Harwood and Nambiar, 2014a). Short-rotation plantations based on fast-growing species represent a relatively new venture in forest management (Vance et al., 2014). Short rotations increase feedstock production for a variety of wood products by enabling more frequent replanting with new clones which are better adapted to different soil and climate conditions, and innovative system management to meet productivity and environmental goals (Harwood and Nambiar, 2014a). Only a relatively small number of tree species are grown as short rotation crops (Harwood and Nambiar, 2014a). Tropical acacia species are especially planted in SE Asia (>2 Mha) for multiple purposes and in response to large-scale wood demands (Harwood and Nambiar, 2014a). These plantations are managed in rotations of 5 – 8 years for pulp wood and up to 10 years for composite products, high veneer logs and sawn timber (Harwood and Nambiar, 2014b). Attributes that make acacia attractive for plantation establishment include its fast growth, adaptation to a wide terrain and climate conditions (van Bueren, 2005; Son, 2006; Kha et al., 2012) and its capability to produce high quality cellulosic pulp for the pulp and paper industries (van Bueren, 2005; Kim et al., 2008).

Biotic threats to plantations in SE Asia

Concerns about the risks of introducing new diseases and pests as plantation forests expand globally are intensifying (van Lierop et al., 2015). Australian acacias and eucalypts planted as non-natives in various parts of the world are increasingly threatened by pests and pathogens as plantation estates age, especially in SE Asia (Wingfield et al., 2011). These include those that are introduced accidentally from the same areas of origin as the trees, as well as 'new encounter' pests and pathogens that are undergoing host shifts to infect the non-native trees. Pests and pathogens do not recognise national borders and shared host species in SE Asia implies shared pest and pathogens. In SE Asia there are a suite of serious biotic problems (Nambiar and Harwood, 2014), often caused by fungal pathogens. In Vietnam, for example, eucalypts, depending on the species, may be susceptible to foliar and stem diseases caused by fungi such as *Cylindrocladium quinqueseptatum, Cryptosporiopsis eucalypti* and *Kirramyces destructans* (Booth et al., 2000; Old et al., 2003). In acacia in Vietnam there are many leaf (phyllode) pathogens that may cause serious damage in the nursery but until recently a stem canker, pink disease caused by the fungus *Erythricium salmonicolor* had the most impact in the field (Old et al., 2003; Thu et al., 2014). Disease symptoms (stem cankers and rapid wilting of trees) were first recognised approximately a decade ago in *Acacia mangium* in Vietnam, Indonesia and Malaysia (Tarigan et al., 2011; Thu et al., 2012; Brawner et al., 2015). These symptoms are caused by a fungal pathogen belonging to the genus *Ceratocystis* and in Vietnam attack all *Acacia* species and hybrids although there is a clear gradient of tolerance (Mohammed in personal communication). Clonal selection of acacia and eucalypts for resistance to disease and high yield is being carried out in Vietnam (Nghia et al., 2010).

Land use history and impact of land use on soil properties in Vietnam

In Vietnam, deforestation from extensive ‘slash and burn’ cultivation and subsequent unsustainable land use have resulted in widespread soil degradation (i.e. erosion, nutrient and organic matter decline) with 9.4 Mha classed as degraded land (Lamb, 2011; Dong et al., 2014). During the period between the 1940s and 1970s, forest cover in Vietnam was reduced from approximately 43% to 17% (De Koninck, 1999); for example, the annual rate of forest loss between 1976 and 1990 was estimated to be 185 000 ha y^{-1} (Barney, 2005). The majority of the studies examining the restoration of degraded forests or fallow lands within the shifting cultivation system by either plantation or natural forest (Vien et al., 2001; Do et al., 2005; Woo et al., 2011) have highlighted the challenges of restoring degraded areas using native species due to their intolerance of infertile soils and a lack of understanding of their physiology (Hung et al., 2010). In this respect, acacia plantations may be useful because they are fast-growing, can produce commercially useful goods and are tolerant of a variety of poorer soils (Turnbull et al., 1997; Nghia and Kha, 1998; Kha, 2003).

Previous studies examining the effect of land use on soil properties have shown that acacia plantations can improve soil nitrogen and soil carbon compared with other land uses, most likely reflecting the capacity of acacia species to fix atmospheric N_2 (Macedo et al., 2008; Kasongo et al., 2009; Yang et al., 2009; Dong et al., 2014). There remain uncertainties in our understanding of the effect of *Acacia* plantations managed in short rotation on soil pH in Vietnam. There is some concern that soil pH decreases under *Acacia* plantations compared to other land uses (Macedo et al., 2008; Kasongo et al., 2009; Yang et al., 2009; Wang et al., 2010; Sang et al., 2013; Dong et al., 2014). In their review of short-rotation acacia plantations in SE Asia, Nambiar and Harwood (2014) concluded that acacia plantations did not cause soil acidification, rather the data of these studies were confounded by site history and sampling methodological errors. Therefore, such research information is needed for land management decisions made by farmers and foresters.

Importance of forestry in Vietnam

Forestry in Vietnam is an important source of revenue for the state's economy (AGROINFO, 2014). In 1986, the Vietnamese government introduced new economic policies based on decentralised and market-driven processes rather than centralised-control model processes (known as Doi Moi) (Nambiar et al., 2015). This new political philosophy promoted the expansion of commercial forestry (Nambiar et al., 2015). Vietnam's wood chip exports supply approximately 38% of the Asian international market and Vietnam is currently the leader in the region (AGROINFO, 2014). The export value of processed and unprocessed wood products including non-timber forest products (e.g. bamboo, rattan) reached over US$6.3 billion in 2014. Approximately 4 M m^3 of raw timber was, however, imported in 2014, or 80% of Vietnam's domestic requirements for sawlog consumption (AGROINFO, 2014). Only 20% of Vietnam's raw timber demand was supplied in-country, mainly from small-scale plantations (AGROINFO, 2014). Continuity of imported raw material supplies for furniture-making was a major concern for the industry. It is clear that Vietnam needs an efficient strategy and practical actions to increase forest productivity, and the quality and value of wood products from existing land under plantations (Nambiar et al., 2015).

Why are Acacia* hybrid *plantations preferred by growers?

Acacia hybrid (*A.* hybrid), the natural hybrid between *A. mangium* and *A. auriculiformis*, is a key multipurpose plantation species that is increasingly being planted across Vietnam for both sawn timber and pulpwood products. According to Sein and Mitlöhner (2011), *A.* hybrid is a medium-sized tree that is capable of reaching a height of 8 – 10 m and a DBH of 7.5 – 9.0 cm within 2 years. An important feature of *A.* hybrid is its high pulping potential and as such the paper produced from this species has better mechanical strength (Kim et al., 2008; Sein and Mitlöhner, 2011). In particular, its pulling and folding strength is markedly superior to paper produced from *A. mangium* or *A. auriculiformis* (Sein and Mitlöhner, 2011). The cellulose content of *A.* hybrid is also markedly higher than that of *Eucalyptus urophylla*, *Eucalyptus camaldulensis* and some native tree species such as *Styearax tonkinensis* and *Manglietia glauca* (Sein and Mitlöhner, 2011). The majority of the planting sites in Vietnam are between 8 – 22 °N, and at an altitude of 5 – 500 m. With regards to climatic conditions, the mean annual rainfall is 1500 – 2500 mm, and mean annual temperature is 23 – 28 °C. From the limited information available, *A.* hybrid can be planted in most lowland areas, especially in central and southern Vietnam, on degraded acidic soils with pH values as low as 3.5 on a wide range of sandy to clay soils (Que et al., 2010; Dong et al., 2014). Results from previous studies have suggested that *Acacia* plantations have the potential to either increase or conserve some key soil chemical and physical properties such as SOC and TN in Vietnam (Dong et al., 2014; Huong et al., 2014; Hung et al., 2016a) but there as mentioned above *Acacia* plantations may exacerbate soil acidification.

According to AGROINFO (2014), in Vietnam the current *A.* hybrid plantation area is approximately 600 000 ha, accounting for 54% of the total acacia area. *Acacia* hybrid is currently planted as a mix of up to three clones (Kha et al., 2012).These plantations are managed in rotations of 5 – 8 years for pulp wood and up to 10 years for composite products, high veneer logs and sawn timber (Harwood and Nambiar, 2014b). However, there is significant variability in *Acacia* hybrid plantation productivity across

Vietnam, most likely explained by marked regional differences in genotype, soils, climate and management practices (Kha et al., 2012; Beadle et al., 2013a; Nambiar and Harwood, 2014). Based on an examination of 30 commercial plantations, Harwood and Nambiar (2014b) reported the mean *MAI* of *A.* hybrid was somewhat lower in the north (mean of 17.6 m^3 ha^{-1} yr^{-1}) than in the south (mean of 23.0 m^3 ha^{-1} yr^{-1}), while the *MAI* in central Vietnam was lowest with a mean *MAI* of 11 m^3 ha^{-1} yr^{-1} (Harwood and Nambiar, 2014b). However, a higher *MAI* (range of 20 – 28.7 m^3 ha^{-1} yr^{-1}) was recently reported for central Vietnam indicating that there is potential to improve productivity of *A.* hybrid within regions (Dong et al., 2014), through improved silvicultural practices.

Management practices of Acacia **hybrid** *plantations*

Typically *Acacia* plantations have been established for pulp production at stocking densities of 1000 – 2500 trees ha^{-1} and managed on a rotation length of 5 – 6 years (Son, 2006; Dung et al., 2013). Site preparation in Vietnam generally involves the burning of post-harvest slash or other vegetation which has often led to reduced soil fertility (Huong et al., 2014). Most growers, particularly small holders, do not use fertiliser for tree plantations due to the high cost of fertiliser, although applying fertiliser has been shown to be crucial if commercial yields are to be obtained, especially on low fertility sites (Son, 2006; Beadle et al., 2013a; Dung et al., 2013; Huong et al., 2014).

Recently, some smallholders and forest enterprises have similarly established similar high initial stockings for sawlogs and managed on a rotation length up to 10 years but without thinning (Beadle et al., 2013b). This practice of high density planting has limited the diameter growth of individual trees because of intense between-tree competition, resulting in small log diameters at harvest. Plantations which are managed for sawlogs carry a higher degree of financial risk than pulpwood plantations as they generally have longer rotation lengths and higher levels of investment than short-rotation pulpwood (Beadle et al., 2015) and most importantly there is uncertainty about the management regimes required for the production of high-value solid-wood products from *Acacia* plantations in Vietnam.

This uncertainty stems from the fact that there has been a relatively short history of research to guide *Acacia* silvicultural practices which, across Vietnam, need to be closely matched to this country's many different environments, types of ownership and desired end products. The last decade has seen some research in Vietnam on silvicultural practices to produce large sawlogs (Son, 2006; Beadle et al., 2013a; Dung et al., 2013) but more research is required. There is also a need for extension activities to be embedded with research as growers must adopt best practice silviculture.

Modelling plantation growth

Historically, empirical modelling approaches based on conventional, mensuration-based growth and yield have been used to forecast forest growth and productivity as well as assist with decision making in forest management (Vanclay, 1998). However, application of empirical models to simulate forest growth under a range of species and environmental conditions is limited (Landsberg and Sands, 2010). In addition, this approach is time consuming, and costly to establish and maintain, and accuracy may be difficult to achieve. These shortcomings have restricted their practical applicability in forest management (Landsberg and Sands, 2010). More recently, forestry productivity has been estimated using alternative approaches based on an understanding of tree growth processes and powerful analytical tools. Specifically, process-based models (PBMs) of forest growth and production are able to describe the plant community processes and interaction between forest growth and their environment (Landsberg and Sands, 2010).

One such model, the 3-PG (Physiological Principles Predicting Growth) model, developed and described in detail by Landsberg and Waring (1997), Sands and Landsberg (2002), and Landsberg and Sands (2010), is a hybrid model that is currently the most widely used PBM. The 3-PG model is freely accessible and information on model parameters and economic uses is widely available for parameterising and validating the model (Almeida et al., 2014). Most importantly, the 3-PG model has demonstrated its practical utility as part of the forest management decision making process (Almeida et al., 2010a). The 3-PG model has been used to reliably predict stand growth and biomass production for a wide range of climate, geographical locations, forest species and management (Landsberg and Sands, 2010). The effects of fertiliser application on forest productivity can be simulated by the model (Almeida et al., 2010a). According to Almeida et al. (2010a), three main areas of application of 3-PG in the decision making process and operation activities are: estimation of potential productivity, forest growth analyses, effects of climate variability and strategic scenarios. However, the application of the 3-PG model to explore the effects of climate, site conditions and silvicultural management at plot and regional scales in tropical forests, especially for acacia, remains scarce, (Morris et al., 2004; Hua et al., 2007; Sang, 2008) particularly when compared to the other more studied species such as eucalypts and pine species (Landsberg et al., 2003; Almeida et al., 2004a). The model was first applied to quantify the benefits of planted forest in Vietnam (Booth et al., 2001). The model was parameterised and calibrated for *A. mangium* using limited experimental data obtained from commercial plantations (Sang, 2008). Therefore, application of the 3-PG model can provide practical information to forest managers on plantation decision making to optimise forest management and determine regional relative potential productivity and sustainability of *A.* hybrid plantations.

The 3-PG model has also been used to map the productivity potential of *A. mangium* plantations under different climate change scenarios (Almeida et al., 2014). Climate change is highly likely to impact on forest productivity over the next century and poses special challenges to forestry (IPCC, 2014). The direction and magnitude of change are uncertain because many factors are changing simultaneously, such as atmospheric composition, temperature, rainfall, and land use (Medlyn et al., 2011). In the last 150 years, the global temperature has increased by 0.76 °C and it is predicted to increase by 3 °C in the 21st century (IPCC, 2014). Global warming is associated with changes in rainfall distribution, climate extremes and sea-level rise (IPCC, 2014). Vietnam is highly vulnerable to sea-level rise and even small rises will have the potential to adversely impact both mangroves and planted coastal forests (Almeida et al., 2010b). Global climate models anticipate significant reductions in rainfall in Vietnam (Hijmans et al., 2005). Moreover, dry seasons under climate change are predicted to become longer, creating more uncertainty about the sustainability of acacia productivity in Vietnam (Almeida et al., 2010b). The predicted longer dry seasons and higher temperatures will create more challenging growing environments and almost certainly compromise *Acacia* forestry unless varieties better adapted to hot conditions and drought stress can be developed (Almeida et al., 2010b).

Research questions

To deal with the above issues, my research used empirical mensuration and modelling approaches to broaden the knowledge of *Acacia* hybrid's response to its environment and its impact on this environment. I improved the applicability and reliability of the 3-PG model for *A.* hybrid. The model can now be used as a tool to better understand and identify management options that the industry can employ to maximise the productivity and sustainability of wood production in Vietnam. The following questions were addressed in my thesis:

1. Can process-based modelling accurately quantify the limiting factors and uncertainties in predicting growth of *A.* hybrid plantations across a wide range of climatic and soil conditions in Vietnam?

2. Can the 3-PG model be used to identify silvicultural practices (thinning and fertiliser application) for improving the production of pulpwood and/or sawlog to provide a more robust and stable source of income from forest products for smallholders?

3. How do soil organic carbon and soil nitrogen change under *A.* hybrid plantations compared with adjacent fallow land within a shifting cultivation system in Northern Vietnam?

1.2. Objectives

The main objective of this study was to assess the productivity and sustainability of short-rotation *A.* hybrid plantations for the generation of wood in Vietnam.

The specific objectives were the following:

1. To estimate productivity of *A.* hybrid plantations for a range of climates and soils in Vietnam.

2. To examine the impacts of alternative silvicultural management practices for maximising profitability of solid wood productions of short-rotation *A.* hybrid plantations that would allow smallholders to optimise the location, timing and silvicultural practices across their plantation base in Vietnam.

3. To evaluate the impacts of contrasting land use (plantation *vs.* fallow land within a shifting cultivation system) on TC and TN content in Northern Vietnam.

1.3. Thesis structure

This thesis comprises of six chapters: a general introduction, a literature review, three experimental chapters and a general discussion with recommendations for future research. The three experimental chapters are written in paper format as they have been, or are intended to be, submitted for publication, and are summarised as follows:

Chapter 1. General Introduction

An introduction to the background and justification of the study approach followed by the defining of the stated objectives.

Chapter 2. Literature Review

The historical and current knowledge and perspectives of tropical *Acacia* plantations in SE Asia is reviewed, identifying the key factors affecting the sustainability and productivity of *Acacia* plantations in Vietnam and focussing on distribution, climate and soil. The applicability of the 3-PG model as a tool in forest management is discussed. Major gaps in knowledge are also identified and are linked to the research questions with a focus on the potential of tropical hardwood plantations, especially of *Acacia* species for supplying wood products to the domestic market.

***Chapter 3.* Predicting productivity of *Acacia* hybrid plantations for a range of climates and soils in Vietnam**

The aim of this chapter was to predict *A*. hybrid growth across Vietnam applying the 3-PG process-based model, and to identify and quantify the factors affecting the productivity of these plantations. The results will assist forest managers and growers to understand the capacity of these landscapes to produce wood, but at the same time to minimise risk and optimise economic and environmental outcomes for this increasingly important species. In this study, we calibrated the 3-PG growth model using ten permanent sample plots located in stands aged 1, 3 and 6 years. The model was then validated using 55 additional permanent plots from 12 plantations growing in four regions that support plantation forestry. The model performed well for most of the validation sites; model efficiencies (*EF*) were ⩾0.76. The model was more accurate in predicting the productivity of plantations in the North and North Central Coast than in the South and South Central Coast regions. Growth was most affected by soil water deficit in this wet/dry tropical environment, than by temperature, particularly in the North. Soil fertility was best predicted by a relationship with soil organic carbon and the base cations Ca^{2+} and K^{+}. Across regions, the mean current monthly increment of stand volume for a 15-yr rotation was 3.21 and 1.97 m^3 ha^{-1} $month^{-1}$ for the wet and dry seasons, respectively. Sensitivity analysis indicated how much the model parameters affect the main outputs and how this changes with stand age. Overall, the model provided an accurate description of the potential productivity of *A.* hybrid plantations across a wide range of climates and soils in Vietnam.

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Chapter 4. **Maximising growth and log size from *Acacia* hybrid plantations in Vietnam**

The growth responses of *Acacia* hybrid plantations to a range of thinning and fertiliser-at-thinning treatments at six experimental trials in North, South Central Coast and South Vietnam were quantified using empirical data and compared to predictive data derived from the 3-PG process-based model. Tree diameter (*DBH*) responses to thinning and stand volume (*SV*) after thinning were greater in the South than in North and South Central Coast Vietnam. Application of fertiliser at thinning increased *DBH* and *SV*, compared with control. Thinning to 450 or 600 trees ha^{-1} resulted in the greatest *DBH* for all diameter classes and was most successful treatment for sawlog production compared to other thinning regimes, with a substantial increase of sawlog volume and the proportion of larger diameter logs. Lighter thinning to 900 or 1000 trees ha^{-1} resulted in comparatively low diameter increments but higher yields of small sawlogs and total *SV* than higher intensity thinnings. The 3-PG process-based model was more accurate in predicting *DBH* and *SV* for all silvicultural treatments at sites in north and central Vietnam, than in the south where productivity was highest. Predictions suggested that *Acacia* hybrid plantations managed for large sawlog production would benefit to growers by extending the rotation length to at least 5 – 7 years in the South and South Central Coast and 6 – 10 years in North Vietnam. The results from this study can be used to minimise rotation length, determine potentially regional productivity and contribute to decision marking for sawlog production from *A*. hybrid plantations in Vietnam.

The full results will be submitted to Forest Ecology and Management as a paper: Hung T.T, Almeida, A.C., Eyles, A., Lam V.T., Mohammed, C. 2016. Maximising growth and log size from *Acacia* hybrid plantations in Vietnam. (Under internal CSIRO review and to be submitted to *Forest Ecology and Management*).

***Chapter 5.* Comparison of soil properties under tropical *Acacia* hybrid plantation and shifting cultivation land use in northern Vietnam**

The aim of this paper was to compare soil properties (SOC, TN, soil pH and soil texture) of contrasting land uses. TN, SOC, pH, bulk densities and particle-size distribution were determined on soil sampled from 25 paired sites with adjacent *A.* hybrid plantations and fallow land within shifting cultivation. The results show that TN and SOC concentrations under the acacia hybrid plantations (AH) were significantly higher at all 10 cm depth increments when compared to the adjacent fallow shifting cultivation lands (FSC). While both these properties decreased significantly with depth in each land use the C/N ratio decreased under the acacia but not the fallow lands. However, there was a significant decrease in soil pH at all depths (>0.4 pH units) which may cause acid infertility issues. While the study has shown that planting *A.* hybrid is an excellent option for the improvement of TN and SOC levels on Acrisols, mitigation of the associated acidification may be required.

This chapter is published: Hung T.T, Doyle, R., Eyles, A., Mohammed, C. 2016. Comparison of soil properties under tropical *Acacia* hybrid plantation and shifting cultivation land use in northern Vietnam. *Southern Forests*. http://dx.doi.org/10.2989/20702620.2016.1225185.

***Chapter 6.* General Discussion, Recommendations and Conclusions**

The results from all chapters are discussed and synthesised, and major findings and conclusions are highlighted. Recommendations on how to improve the productivity and sustainability of *A.* hybrid plantations in Vietnam are presented. The chapter concludes by outlining future priority research directions and opportunities for increasing the economic viability and sustainability of *A.* hybrid plantations for smallholder forestry in Vietnam.

CHAPTER 2

LITERATURE REVIEW

CHAPTER 2. LITERATURE REVIEW

2.1. Distribution and importance of Asian hardwood plantations

2.1.1. Distribution

Productive and protective plantations, together with semi-natural planted forests (SNPFs), constitute the subgroup ‘planted forests’, as defined in FAO’s global forest resources assessments 2010 and 2015. In many developing and developed countries, planted forests have become a substantial component of the productive and protective forest resources and play an ever more important part in securing both industrial roundwood and wood fuel (Payn et al., 2015; Sean and Jeffrey, 2015). The FAO (2015) estimated that planted forest in Asia has increased to 30 Mha over the past ten years. In particular, there are 25.6 Mha of tropical plantations accounting for 8.7% of the total forest area in South and South-East Asia (Payn et al., 2015). The majority of plantations are in China, India, Indonesia, Malaysia, Thailand and Vietnam, representing 90% of the total area of tropical plantations (Figure. 2.1) (Payn et al., 2015).

The main plantation genera that have been planted in the past two decades in tropical South-East Asia are *Acacia* and *Eucalyptus*, with plantations now totalling approximately 7 Mha, of which around 2.6 Mha is *Acacia* and 4.3 Mha is *Eucalyptus* (Nambiar and Harwood, 2014). Areas of *Eucalyptus* plantations are largest in China and there are estimated to be over 4 Mha (Table 2.1). Until recently with the advent of *Ceratocystis* canker and wilt disease *Acacia mangium* was the preferred species in many regions of SE Asia (Eyles et al., 2008; Mohammed et al., 2014). Areas of *A. mangium* plantations in Indonesia increased from 0.6 Mha in 1998 – 1999 to about 0.8 Mha by

2011 (Hardiyanto and Nambiar, 2014). In 2013 there were approximately 1.4 Mha of *A. mangium*, mainly in Indonesia and Vietnam (Table 2.1). *Acacia crassicarpa*, 0.5 Mha reported in 2013 (Table 2.1), is mainly planted in Indonesia's peatland as *A. mangium* does not thrive in peatland soils (Mohammed et al., 2014). Pulp production from *Acacia* plantations is the largest in Indonesia and is estimated to reach about 16 M t year^{-1} by 2020, requiring an additional 9 Mha of plantations (Hidayati et al., 2014). In 2013, the estate of *Acacia* in Vietnam was estimated at 1.1 Mha which included 0.6 Mha of *A. mangium*, 0.09 Mha of *Acacia auriculiformis* and 0.4 Mha of *A.* hybrid (Nambiar and Harwood, 2014).

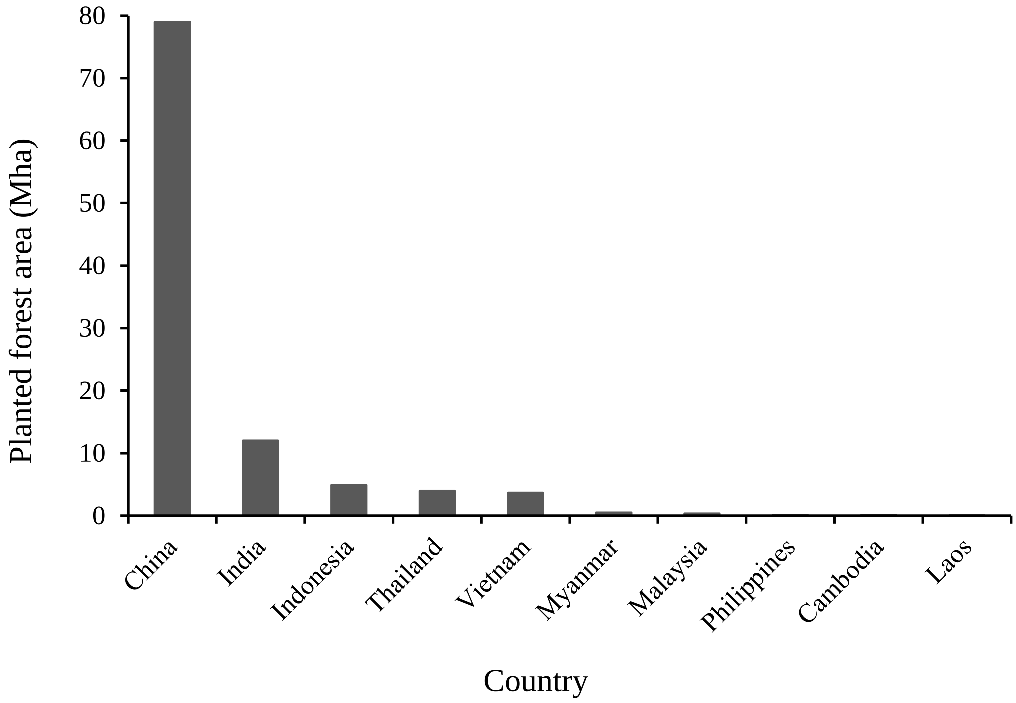

Figure 2.1 Area of planted forests in 2015 in South-East Asia (Payn et al., 2015).

Table 2.1 Area of major species planted in 2013 in South-East Asia (Nambiar and Harwood, 2014).

Species	Country	Area (ha)
A. mangium	Indonesia, Vietnam, Malaysia	1 350 000
A. auriculiformis	Vietnam	90 000
A. hybrid	Vietnam	400 000
A. crassicarpa	Indonesia, Vietnam, Malaysia	700 000
E. dunnii	China	60 000
E. grandis	China	60 000
E. hybrid	China, Thailand	4 000 000
E. globulus	China	120 000
E. pellita	Indonesia	300 000
E. camaldulesis	Thailand	500 000
E. urophylla	Vietnam	200 0000

2.1.2. Importance of tropical hardwood plantations

The growth of Asia's substantial industries based on industrial roundwood has to be underpinned by a large area of sustainably grown local plantations (Cheng and Le Clue, 2010). According to Payn et al. (2015), the production of industrial roundwood in planted forests in 2012 in Asia was 151 M m^3; China (64.2 M m^3), India (43.1 M m^3), Thailand (14.6 M m^3) and Indonesia (12.5 M m^3) (Jürgensen et al., 2014). While pulpwood and paper are the dominant products, production of small logs for a range of solid and engineered wood products is increasing, for example, eucalypt sawn timber in China and acacia in Vietnam (Harwood and Nambiar, 2014a).

Forests contribute to ecosystem services like fresh water, clean air, biodiversity, landscape beauty and greenhouse-gas mitigation by the capture of carbon (Phuong, 2011). Forest plantations are mainly managed wood and fibre products and are not developed as functional ecosystems (Thompson et al., 2014). The trade-offs between the commercial production targeted by forest plantations and ecosystem services may be challenging and plantation forests often have a negative image (Phuong, 2011). Yet tropical hardwood plantations can and should play a role in the provision of ecosystem services (Phuong, 2011), especially when compared to agriculture or degraded natural forest. The issue of deforestation and soil erosion in north and central Vietnam is being addressed with a successful afforestation model based on public and private sector collaboration and focusing on income generation for poorer households (Phuong, 2011).

2.2. Historical and current perspectives of forestry in Vietnam

2.2.1. Previous land management

Deforestation and unsustainable land use have created large expanses of degraded land in several countries in the Asia-Pacific region including Vietnam (Lamb, 2011). In Vietnam 9.4 Mha are currently classed as degraded land (Lamb, 2011; Dong et al., 2014). During the period between 1944 and 1992, forest cover in Vietnam was reduced from 43% to 28% of land area (De Koninck, 1999; McNamara et al., 2006). During the Vietnam War (1962-1975), US military actions destroyed an estimated 4.9 million hectares of forest cover. The annual rate of forest loss between 1976 and 1990 was 185 000 ha yr^{-1} (Barney, 2005). Reforestation has been thwarted by forest fires, the collection of firewood, and the over harvesting of timber (often illegal) and unplanned agricultural clearances (Lamb and Gilmour, 2003). In the mountainous regions of

Vietnam, shifting cultivation (slash-and-burn or swidden agriculture) has been commonly practised for centuries by 54 ethnic minorities, mainly H'Mong and Dao groups, across an area of 3.5 Mha (Sam, 1994; Do et al., 2011). Under the pressures of increasing populations and land scarcity, this traditional shifting cultivation system has changed from short cultivation – long fallow periods to long cultivation – short fallow periods resulting in increased soil erosion and a decline in soil fertility (Vien et al., 2001; Wezel et al., 2002; Do et al., 2011).

The majority of the studies examining the restoration of degraded forests or fallow lands within the shifting cultivation system by either plantation or natural forest (Vien et al., 2001; Do et al., 2005; Woo et al., 2011) highlighted the challenges of restoring degraded areas using native species due to their intolerance to infertile soils and a lack of understanding of their physiology (Hung et al., 2010). This difficulty in using native species led to the introduction of monocultures of fast-growing exotics including *Eucalyptus* and *Acacia* species (Binh et al., 2004).

Commercial forest plantations of *Acacia* and *Eucalyptus* species are therefore relatively new in Vietnam but in 1986 the introduction of a new political philosophy (Doi Moi) that based economic growth on decentralised and market-driven processes rather than a centralised-control model process promoted their expansion (Nambiar et al., 2015). In 1998, Vietnam launched a huge national program that aimed to re-establish 5 Mha of forest by 2010, 2 Mha for protection of water resources and special-use forests and 3 Mha for commerce (MARD, 2010). As a result of the latter initiative and similar foreign aid supported programs, in 2010 forest cover in Vietnam was estimated to have increased by 18% and to be 39% of total land area (MARD, 2010).

Vietnamese forestry is currently associated with a diverse range of stakeholders, different types of forest management and business models. Nearly half (46%) of the total plantation area in Vietnam is managed by approximately 250 000 individual smallholders, each typically with less than 5 ha of forest plantation. The smallholder growers comprise local people and forest workers who invest in plantations to supplement their long-term household income from agro-forestry systems (Kien et al., 2014). Other stakeholders include management boards for protection forests and special-use forests (17%), state companies (15%), private companies (4%), people's committees at a provincial level (12%) and other minor players (Kien et al., 2014). Land ownership of special forests is determined by certificates of land rights issued by the Vietnamese government (Phuc et al., 2013) and this system minimises conflicts in land use and harvesting rights. State companies, individual households and people's committees are the largest forest owners among these owner groups, but they seldom manage more than 5000 ha in total and their holdings are often dispersed in small parcels of land (Nambiar et al., 2015). Wood transport, processing and marketing are managed by many small- and medium-sized businesses (Nambiar et al., 2015).

2.2.2. Current policies on plantation expansion

In 2010, the Vietnamese Government announced policies to support the development of the forestry sector for the period between 2011 and 2020 (MARD, 2010). These policies aim to protect the 13.4 Mha of existing natural forest and plantations as well as increase forest cover to 45% of total land area by 2020. Before the ban on harvesting of natural forest in 1990 the timber harvested from both natural and plantation forests was 4 – 4.5 M m^3 yr^{-1} (MARD, 2015). The timber harvest from plantations alone is currently 2 – 3

M m^3 yr^{-1} (MARD, 2015). Access to new land suitable for commercial plantation forestry is limited (MARD, 2010) as government policy restricts further clearing of degraded native forests for plantation establishment and existing plantations face competition from other land uses including agriculture and rubber plantations (Nambiar et al., 2015). Future growth in wood production and processing industries will strongly depend on increasing and sustaining productivity on the current plantation land base, with due environmental care (MARD, 2010).

2.2.3. Economic importance of Vietnamese wood product industries

Vietnam's wood processing industry is well known for production and exports of high-end wood products, particularly furniture. Vietnam is one of the world's largest exporting countries of wooden furniture and parts, with exports valued at $US 6.5 billion in 2014 (AGROINFO, 2014), whereas the exports of primary timber products were valued at 769.8 million US dollars in 2014 (AGROINFO, 2014). Viet Nam has about 3,000 wood processing enterprises, 95% of which are privately-owned. The relatively low cost labour force and a favourable environment for foreign investment are the main competitive advantages of the Vietnamese industry. Besides furniture the main export products of the Vietnamese wood product industries are wood chips and paper, with Vietnam being one of the biggest wood chip exporting countries of the world (AGROINFO, 2014).

Approximately 4 M m^3 of raw timber was, however, imported in 2014 from other countries such as Malaysia, Brazil, China and Laos. At least 80% of this imported wood volume was re-exported (AGROINFO, 2014). With the increasing domestic and international demand for timber furniture many plantation growers plan to divert all or part of their production to sawlogs (Kien et al., 2014) especially as there are significant economic advantages of sawlog over pulpwood production for small-land holders (Blyth and Hoang, 2013). In Vietnam, straight logs with small-end diameters exceeding 15 cm are commonly sawn and fetch a stumpage price up to twice that of pulpwood (Harwood, 2011). For example, prices of pulpwood and sawlogs are AUD 23 m^{-3} and AUD 67 m^{-3}, respectively (Blyth and Hoang, 2013). In 2013 in southern Vietnam average stumpage prices for standing acacia timber were estimated to be USD 32.1 m^{-3} for pulpwood <10 cm diameter, USD 39.2 m^{-3} for small sawlogs 10 – 18 cm and USD 85.1 m^{-3} for large sawlogs >18 cm (Beadle et al., 2015). The higher the proportion of sawlogs with large diameter at final harvest, the greater the financial return to the small holder (Beadle et al., 2015).

2.3. Selection of plantation species in Vietnam

The problems in restoring degraded areas using native species (Hung et al., 2010) and the need for fast growing plantation species to meet demand led to the introduction of the exotic species *Eucalyptus* and *Acacia* (Binh et al., 2004). Table 2.2 shows improved *Acacia* and *Eucalyptus* clones of superior genotype are currently planted across Vietnam.

Table 2.2 Selected *Acacia* and *Eucalyptus* clones of superior genotype (MARD, 2001).

Species	Clones	Use
A.mangium	M2	Pulpwood, sawlogs, fuel wood
A. auriculiformis	Clt7, Clt18, Clt19, Clt25, Clt26, Clt43, Clt57, Clt58, Clt62, Clt64, Clt98, Clt133, Clt171, Clt1C, Clt1E, Clt1F, AA1, AA6, AA7, AA9, AA10, AA12 and AA15	Pulpwood, sawlogs, fuel wood
A. hybrid	BV10, BV16, BV32	Pulpwood, sawlogs, fuel wood
E. urophylla	PN10, PN46, PN47, PN46, PN108 and PN3D	Pulpwood, sawlogs, fuel wood
E.camaldulensis	C9, C55, C159 and BV22	Pulpwood, sawlogs, fuel wood

Early plantings of *E. camaldulensis* and *E. tereticornis* did not grow well in Vietnam, especially on degraded soils, resulting in a preference for *Acacia* species because they are also fast-growing but can improve nitrogen fertility and grow better on degraded soils by their ability to fix N_2 (Kha et al., 2012). This concern of low productivity in *Eucalyptus* was partially addressed in the early 2000s when breeding led to improved genetic material including hybrids of *E. pellita* and *E. urophylla* (Son, 2006) with disease resistance and higher productivity (Nghia, 2003; 2010). Growers are now more willing to grow eucalypts, especially in the northern sites where growth rates of eucalyptus may even be higher than acacias (MARD, 2010). More specific information is however required about the determinants of productivity for *Eucalyptus* species and clones under the very different environmental and management systems in Vietnam (Hung, 2014).

Acacia species were first introduced to southern Vietnam in the 1960s and to northern Vietnam in the early 1980s from their natural habitats in northern Australia and Papua New Guinea (Kha, 2001). Attributes that make *Acacia* species attractive for plantation establishment include good growth rates on a range of sites including on shallow, stony soils (Kha, 2001, 2003; Nghia, 2003; van Bueren, 2005; Son, 2006; Kha et al., 2012) as well diverse uses such as the provision of high quality pulp and the production of high-value furniture (van Bueren, 2005; Kim et al., 2008). *Acacia* species are favoured by smallholders with more limited financial and technical resources as they are easier to grow and manage than *Eucalyptus* (Kha, 2003).

Acacia breeding focused initially on adaptability to site, growth rates and stem form (Kha 2001). By around 2005, breeding of pure-species of *A. auriculiformis*, *A. mangium* and *A. crassicarpa* had advanced to the second generation and field evaluation showed substantial genetic gain in productivity for selected first-generation seed lots, relative to natural and local commercial seed sources (Hai et al., 2008a; Nambiar et al., 2015). Selected clones of *A. auriculiformis* now planted in Vietnam have improved stem straightness as well as vigour, relative to previously planted seed sources (Hai et al., 2008b).

FAO (1982) first reported natural hybridisation between *A. mangium* and *A. auriculiformis* (*A.* hybrid) in the late 1970s, in Sabah, Malaysia. In nature, *A.* hybrid is found at sites with a mean annual temperature of 12 – 35 °C, an annual rainfall of 1200

– 1850 mm and an elevation of 50 – 350 m (Nghia and Kha, 1998; Sein and Mitlöhner, 2011). A clonal trial of *A.* hybrid in the early 2000s showed good performance for a range of site conditions across Vietnam (Kha, 2003). The further development of productive clones of *A. mangium* × *A. auriculiformis* hybrids and propagation systems in Vietnam for country-wide deployment has been a major achievement (Kha et al., 2012).

2.4. Current management of *Acacia* grown for sawlogs

Prior to the early 1990s, research on *Acacia* species largely focused on tree genetics and breeding. Since 1993, research also included site and stand management and this shift in focus came about as a result of several national research programs which examined how productivity could be improved through site management of soil and stand (Kha et al., 2012). From this research, *Acacia* plantations are currently managed in rotations of 5 – 8 years for pulpwood and up to 10 years for composite products, high veneer logs and sawn timber (Nambiar and Harwood, 2014; Nambiar et al., 2015). However, management practices vary according to ownership and location of plantations. In central and northern parts of Vietnam, the majority of plantations are on high slope and hilly terrain (Son, 2006; Kien et al., 2014). In much of Vietnam, in particular the centre and north of Vietnam, manual labour and simple tools are used for site preparation, tending and harvesting (Son, 2006; Nambiar et al., 2015). In flat regions (mostly in south Vietnam), manual labour combined with machinery is used (Dung et al., 2013). Across Vietnam, site preparation traditionally involves the burning of post-harvest slash and vegetation (Kien et al., 2014). It is recognised that inter-rotational practices (e.g. slash retention or burning) that are adapted to the many different forest growing environments of Vietnam are key to maintaining and improving the site's productivity (Son, 2006; Kien et al., 2014) and research about inter-rotational practices is the focus of current research (Dung et al., 2013; Huong et al., 2014).

Seedlings or clones are planted in 40 cm × 40 cm × 40 cm holes (Kha et al., 2012). Weed control either by manual labour and/or herbicide application is carried out at least twice a year during the first two years of planting. Further weed control may be required for less productive sites (Son, 2006). The most suitable stocking rate for pulpwood plantations in Vietnam ranges between 1111 to 2500 trees ha^{-1} (Harwood et al., 2007). Higher initial stocking densities reduce the incidence of heavy branching in plantation hardwood species (Neilsen and Gerrand, 1999) but may lead to a reduction in the average growth of individual trees. A close spacing of 2.0 m × 2.0 m or 2.5 m × 2.5 m is often preferred by Vietnamese smallholders to maximise standing volume (Son, 2006; Thuyet, 2010) and encourage branch shedding. However, depending on the level of information and expertise available, tree spacing may be modified according to the intended purpose of the trees and/or quality of the sites and especially if the intention is to thin and prune for timber products.

In commercial forestry, straight stems are an important management goal especially for the production of sawlogs and any factors which may induce stem deformation, heavy branching and stem breakage are to be avoided. Although *Acacia* has a reasonable level of apical dominance, variable numbers of individuals are multi-stemmed at the base, the proportion probably related to genotype and site conditions (Srivastava, 1993). Management practices affect crown and branch development and stem form in young *Acacia* plantations; the choice of genetic material (clones), age and physiological condition of stock plants, dose and application method of fertiliser and initial plantation stocking density, singling, pruning and thinning (Beadle et al., 2007; Beadle et al., 2008; Forrester et al., 2012; Beadle et al., 2013a). Silvicultural practices such as singling, pruning and thinning and their interactions with the environment and silvicultural practices are of crucial importance in certain plantation species such as *Eucalyptus* and *Acacia* in order to optimise the number of straight, larger diameter and knot-free sawlogs that are grown (Arisman and Hardiyanto, 2006; Beadle et al., 2007). Without thinning, in North Central Vietnam, survival rates 9.5 years after planting were approximately half the initial stocking rates of 1330, 1660 and 2500 trees ha^{-1} and the percentage of trees with a diameter ⩾18 cm with were 38%, 25% and 20% respectively (Dung et al., 2013).

The non-shedding of branches in plantation *Eucalyptus* and *Acacia* results in the development of unwanted knotty cores that greatly reduces the amount of clear wood recovered for select grade material (Waugh, 1996; Beadle et al., 2007; Beadle et al., 2013a). Large branches in *Eucalyptus* and *Acacia* in the pruning zone of the stem may also be associated with a high risk of decay entry, making it especially important to control the size of branches to be pruned (Beadle et al. 2007; Weinland and Zuhaidi (unpublished, see Srivastava, 1993)).

Singling is an essential practice in *Acacia* plantations for the creation of single stems. This is because these acacia species tend to have moderate apical dominance at best; removal of competing stems and branches artificially transfers dominance to the selected leader (Beadle et al., 2007). Lift prunin**g** is defined as the removal of lower green branches to a predetermined height (Beadle et al., 2007). Form pruning involves the selective removal of branches throughout the crown and can be used to reduce average branch size before a subsequent lift pruning (Pinkard, 2002) or to correct potential deviation of stems from a pathway of vertical growth (Nicholas and Gifford, 1995; Medhurst and Beadle, 2005). Form pruning is carried out before canopy closure occurs to increase the numbers of trees that meet the requirements for lift pruning (Beadle et al., 2007). Lift pruning is absolutely necessary for the production of clear or knot-free wood in *Acacia*. As this exposes pruning wounds on the stem, best practice is to lift prune only in the dry season to minimise risk of disease entry. This can be made to work if used in tandem with a modification of form pruning. Tip pruning that removes around 50% of the competing leader or branch length can be used as form pruning (Beadle et al., 2013a). This is adequate for controlling branch size and establishing or maintaining dominance in the selected leader and avoided the creation of exposed pruning wounds on the stem in the wet season. These form-pruned branches could then be removed at the stem through lift pruning in the dry season. Observation suggested that there was no penetration of decay down the length of the cut branch between the time of tip pruning and time of lift pruning. No more than 30% of the green crown length in *A.* hybrid should be removed in a lift (Beadle et al., 2013a) as severe pruning can reduce growth, even for fast-growing species such as *Acacia* species. Beadle et al. (2013a) recommended that a first lift pruning in *A.* hybrid should be undertaken at the time of canopy closure when the trees are 7 – 8 cm DBH to a pruned height of 2 – 2.5 m. The second lift pruning is up to 4.5 m and when the tree is 10 – 11 m. The third lift pruning to produce a 6 m log is up to 6.5 m and occurs when the tree is 12 – 14 m.

Form pruning has been compared with lift pruning in *Acacia* plantations. Beadle et al. (2007) in a trial in Indonesia observed that when 25% of the leaf canopy was removed by form or lift pruning in 1.5-yr-old *A. mangium* trees, form pruning was associated with better form after 18 months than lift pruning which reduced average branch size but did not improve stem straightness. In Central Vietnam there were no significant differences between the two types of pruning in *A.* hybrid two years after pruning (Thang et al., 2011) but the observations were based on height and diameter not form. In another *A.* hybrid plantations in Central Vietnam form pruning was associated with a reduced incidence of wood defects (Thuyet, 2010).

Thinning is defined as the process of removing or harvesting selected trees to encourage the remaining trees to maximise growth rate (Beadle et al., 2013b; Beadle et al., 2015). Stand quality in *Acacia* is improved though thinning by removing deformed trees and reducing the time taken for trees to reach valuable sized sawlogs (Hardiyanto, 2006). Thinning operations in *A.* hybrid are usually conducted when a plantation is three, five and seven years old (Son, 2006).

Marked increases in diameter and height have been reported by several authors. The diameter growth of a 5-yr-old *A.* hybrid plantation in southern Vietnam was significantly increased 2 years after thinning from 1333 to 475 trees ha^{-1} (Son, 2006). Dung et al. (2013) in the same region found that the total basal area of an *Acacia* hybrid trial thinned to 600 trees ha^{-1} was similar to that of unthinned trees, but the diameter of the thinned trees was significantly higher than that of unthinned trees. In Central Vietnam a doubling in the volume of six-month-old *A.* hybrid observed 2 years after thinning was observed by Beadle et al. (2013a) although height was not significantly impacted by thinning.

The interactions between initial stocking rates, thinning intensity and timing of thinning are important considerations. Only a few studies have investigated different thinning regimes. Progressive thinning from 1667 tree ha^{-1} to 750 – 900 trees ha^{-1} in year 4 then to 550 – 700 trees ha^{-1} in year 7 (Thuyet, 2010) allows 92 – 96% of stems to reach a diameter of ⩾18 cm after 12 years although the total standing volume is lower compared with a plantation of higher density.

Generally, fertiliser is applied at planting and six months after planting. Most growers in Vietnam, particularly small households, cannot afford to use high rates of fertiliser (Son, 2006; Huong, 2016). Based on several studies and the other research there is no reason to resort to high rates of fertiliser application for healthy *Acacia* growth although judicious applications of fertiliser may be recommended on low fertility sites or for sustaining productivity in the second and subsequent rotations (Nambiar et al., 2015; Bon and Harwood, 2016; Huong, 2016). Bon and Harwood (2016) reported that 10 – 15 g P $tree^{-1}$ at planting is adequate at most sites to achieve a noticeable improvement in early height growth and maintain growth throughout the rotation. Higher doses of fertilise applied include 25.0 g N, 25.0 g P, 20.7 g K and 100 g microorganism-enriched fertiliser per seedling (Harwood et al., 2007). Authors such as Son (2006) have reported that growth rates are improved with high rates of fertiliser e.g. with 200 g of N:P:K 16:16:8 and 100 g of microorganism- enriched fertiliser at planting, the annual volume increment of *A.* hybrid was 36.7 m^3 ha^{-1} yr^{-1} at age 6 years compared to 28.8 m^3 ha^{-1} yr^{-1} without fertiliser treatment. However these authors do not report on the influence of high fertiliser rates on form. Bon and Harwood (2016) found that high doses of fertiliser at planting significantly increased the proportions of trees requiring singling and form pruning, the diameter of the largest branch in the 1 – 2 m stem height interval, and the severity of stem bending and breakage. These authors suggested that high doses of fertiliser at planting should be avoided for *Acacia* hybrid plantations. There is very little information about the interactions between thinning and fertilisation.

It is well known that a plantation's capacity to supply sufficient quantities of appropriate diameter classes for sawlogs will depend on the physiology of the host and the interactions between site properties and silvicultural regimes; fertilisation, pruning and thinning (Glencross et al., 2011; Cassidy et al., 2012; Beadle et al., 2013a). However thinning and pruning have not been routinely practised in Vietnamese plantations due to the prohibitive costs of the silvicultural operations thinning. Fertilisation is also costly. Management practices vary enormously among the smallholders. To date, there has been little work done in establishing national standardised operational and cost effective procedures in Vietnam. Access to improved information and technological support by smallholders can only enhance their long-term prospects and improve the sustainability of plantations (Nambiar et al., 2015) but much of the research remains to be done.

2.5. Effects of climate on growth of *Acacia* plantations in Vietnam

Climates vary greatly within Vietnam. The extensive variation in altitude and latitude, and the effects of mountain ranges on monsoon systems, result in substantial differences in rainfall and temperature regimes. The majority of the plantations are currently established on low topography and easily accessible sites that receive an annual rainfall >1500 mm, which exceeds annual evaporation <1500 mm (MARD, 2001, 2015). Tropical environments in Vietnam are associated with a distinct dry season (Nghia, 1996). In central and Southern Vietnam there is a distinct dry season of up to seven months when seasonal water deficits constrain growth (Kha et al., 2012) and can have a marked impact on the intra-seasonal growth of acacias. For example, despite a mean annual rainfall of 2250 mm yr^{-1}, the stem diameter increment of *A. auriculiformis* (age three and a half years) can be less than 0.5 mm $month^{-1}$ during the dry season in South Vietnam. In contrast, stem diameter increments of two to three mm $month^{-1}$ are typical during the wet season (Huong et al., 2008). The majority of the studies examining the relationships between the productivity of *Acacia* plantations and climate show that it is not sufficient to define suitable climates for *Acacia* plantations by mean annual rainfall alone; the length and severity of the dry season, indicated by mean monthly rainfall and pan evaporation, are critical to their success or failure (Harwood, 2011). Seasonal changes in temperature and vapour pressure deficit also influence *Acacia* growth although they have less impact than rainfall (Almeida et al., 2010b). Kha (2003) reported that the climate is more favourable to grow acacias in the South where the temperature is close to the optimum and has less limitation during the winter months than in the North and Central regions. Booth et al. (2001) found that acacias are grown well in Vietnam, where mean annual temperature ranges from 22 – 30 °C and 22 – 28 °C.

While *Acacia* species can be productive in a wide range of environments, a major concern is the push to plant in drier landscapes and onto poorer soils. The planting of *Acacia* into such marginal locations has not yet been underpinned by research. The need for such research is urgent. Under climate change for Vietnam significant reductions in rainfall are predicted (Hijmans et al., 2005) as well as an increase in the length of dry seasons (Almeida et al., 2010b). The sustainability of the plantation industry under drier and more marginal growing conditions is uncertain (Almeida et al., 2010b).

2.6. Effects of key soils on growth of *Acacia* plantations in Vietnam

2.6.1. Soil types and soil depths

Most Vietnamese soils are classified as Acrisols and Ferralsols (Sang et al., 2013) which are the most extensive soil types in Southeast Asia (FAO, 2006). According to Sang et al. (2013), Acrisols are characterised by deeply weathered acid profiles with low base saturation to depth and low activity clays with low to moderate natural fertility. Ferralsols are characterised by strongly weathered parent materials, high content of sesquioxides, good physical and poor chemical properties to some depth. Both soils are clay rich but generally of low fertility, porosity and hydraulic conductivity.

Productivity i.e. mean annual increment (*MAI*) in *Acacia* plantations has been found to markedly vary and is largely related to site characteristics such as soil type, soil depth and elevation and climate (Hung et al., 2016b). The growth rates of all *Acacia* species are generally greater in South and Central Vietnam than in North Vietnam (Nghia and Kha, 1998; Kha et al., 2012). *MAIs* of *Acacia* plantations have been shown to vary between 15 m^3 ha^{-1} yr^{-1} on infertile soils to >30 m^3 ha^{-1} yr^{-1} on fertile soils (Harwood et al., 2007; Kha et al., 2012). Sang et al. (2013) found significant effects of five soil types (Ferralic Acrisols, Dystric Cambisols, Ferric Acrisols, Xantric Ferralsols and Haplic Acrisols) on the productivity of *A. mangium* plantations at age 8 years. This study found that Dystric Cambisols and Ferralic Acrisols had the highest values of soil properties associated with the good growth of *A. mangium* (total soil C concentration, N content and extractable P levels) while Haplic Acrisols showed the lowest values for these properties. Table 2.3 shows the *MAIs* obtained on different soil types across Vietnam but productivity may also be linked to site characteristics other than soil type.

A preliminary examination of the relationship between soil depths and potential productivity in Vietnam was done by Sam (2001) (Table 2.3). For example, the MAI of *A. mangium* at age eight years was shown to increase with soil depths on an Orthic Ferralsol soil at the North Vietnam. In particular, the *MAI* was 6, 15.7 and 25.7 m^3 ha^{-1} yr^{-1} when the soil depth was <50, 80, and >100 cm, respectively (Sam, 2001). The *MAI* of *A. mangium* at age eight years at the South Vietnam ranged 16 – 22 m^3 ha^{-1} yr^{-1} on a > 100 cm-depth Orthic Acrisol in Binh Duong, while the *MAI* at Dong Nai ranged 15 – 19 m^3 ha^{-1} yr^{-1} on a <50 cm-depth Ferric Acrisol. The *MAI* of *A. auriculiformis* at age nine and a half years was 12 – 16 and 6 – 10 m^3 ha^{-1} yr^{-1} on an Orthic Acrisol of >100 and <50 cm depth, respectively (Sam, 2001). The growth rate of *A. auriculiformis* at age 8 years was 9 – 10 m^3 ha^{-1} yr^{-1} on a degraded Rhodic Ferralsol in the Central Highlands, in part, associated with the higher elevation (800 m) (Sam, 2001).

Table 2.3 Relationships between soil types, soil depths and productivity in *Acacia* and *Eucalyptus* plantations in Vietnam.

Regions	Species	Stand age (year)	Soil types	Soil depths (cm)	Stocking (trees ha^{-1})	*MAI* (m^3 ha^{-1} yr^{-1})	References
North	*A. mangium*	8 – 16	Orthic Ferralsols, Ferralic Acrisols, Dystric Cambisols, Ferric Acrisols	<50 – >100	1100 – 1667	6.0 – 25.7	(Sam, 2001; Sang, 2008)
	A hybrid	4 – 7	Ferric Acrisols, Haplic Acriols		1111 – 1667	10.5 – 17.1	(Sam, 2001; Beadle et al., 2013a)
	E.urophylla	4 – 8	Orthic Ferralsols	<50 – >100		5.6 – 13.7	(Sam, 2001)
Central	*A. mangium*	6 – 8	Rhodic Ferralsols, Ferric Acrisols, Haplic Acriols, Dystric Cambisols	<50	1667	6.0 – 29.0	(Sam, 2001; Sang, 2008)
	A.auriculiformis	8	Rhodic Ferralsols		1667	9.0 – 10.0	(Sam, 2001)
	A hybrid	1.5 – 5	Acrisols		1111 – 2000	7.0 – 28.7	(Beadle et al., 2013a; Dong et al., 2014)
South	*A. mangium*	4 – 8	Orthic Ferralsol, Ferric Acrisols, Haplic Acriols	>100	1667	10.0 – 31.0	(Sam, 2001; Sang, 2008)
	A.auriculiformis	5 – 9.5	Orthic Acrisol, Ferric Acrisol, Chromic Acrisols	<50 – >100	833 – 1667	6.0 – 33.9	(Sam, 2001; Huong et al., 2014)
	A hybrid	3 – 5	Ferralic Acrisols, Chromic Acrisols, Gleyic Acrisols			15.0 – 25.7	(Beadle et al., 2013a)
	E.camaldulensis	5	Orthic Ferralsol	>50		5.8 – 29.0	(Sam, 2001)

2.6.2. Soil organic carbon

Soil organic matter (SOM) is any soil material that comes from the tissues of organisms (plants, animals, or microorganisms) that are currently or were once living. Soil organic matter is rich in nutrients such as nitrogen (N), phosphorus (P), sulfur (S), and micronutrients, and is comprised of approximately 50% carbon (C) (FAO, 2006). Soil organic carbon (SOC) refers specifically to the carbon element of the soil organic material. Soils hold the largest store of carbon in the terrestrial environment (Jobbagy and Jackson, 2000).

Organic matter in the soil can be described as fresh and decomposing plant residues, decomposed humic materials, and a small amount of living microbial organisms (Bouwman, 1990). The latter is transported carbon to the lower depths of the soil profile through the decomposition of plant residues. A significant proportion of organic matter will be quickly decomposed in the upper layers of the soil and carbon returned to the atmosphere as CO_2 (Sumner, 1999). This efflux or 'soil respiration' is an important factor in the cycling of soil carbon (Schlesinger et al., 2000). The remaining SOM which is less readily decomposed undergoes the slower process of "humification", or decomposition that produces a set of humic substances (fulvic acid, humic acid and humus) which are chemically stable and resistant to further breakdown (Ghabbour and Davies, 2005). Relatively little of the initial carbon input to the soil ends up as humus and processed soil organic matter such as this belongs to what is known as the "recalcitrant carbon" pool; a long-term store of stable organic carbon with a mean residence time (MRT) of potentially thousands of years (Cheng et al., 2007). The "labile carbon" pool is associated with organic material with a much shorter MRT and includes plant residues and rapidly decomposing detritus. The dynamics of the soil carbon pool and its origins in above- and belowground plant biomass result in a vertical distribution of organic carbon that decreases with depth (Jobbagy and Jackson, 2000). The allocation of carbon within the soil profile varies greatly with location, the main controls on which are thought to be climate, soil type, vegetation, land use and its history and, specifically in forestry, silvicultural regimes (Jobbagy and Jackson, 2000; Sang et al., 2013; Anh et al., 2014; Dong et al., 2014). These controls are thought to have the strongest impact upon the top 0.2 metres (m) of soil (Jobbagy and Jackson, 2000).

Soil texture, moisture, structure, fertility and preservation capacity influence SOC (Bouwman, 1990). Heavy-textured and coarse soils may slow decomposition and/or limit the movement of microorganisms and therefore slow rates of SOC storage (Bouwman, 1990). Fine clay soils provide the best environment for SOC storage owing to their negative surface charge which facilitates the adsorption of nutrient cations and a linear relationship between clay content and SOC has been recognised (Schimel et al., 2000). Water saturation favours reduction over oxidation processes, which is unfavourable to the soil organisms decomposing plant debris and decreases the possibility of SOC storage (Rutherford et al., 1997). Fertile soils rich in minerals will favour quick decomposition (Bouwman, 1990). High mineral content occurs when fertilizer is applied and when plant root uptake is minimal, and results in the stimulation of microorganisms (Bouwman, 1990).

Nitrogen-fixing tree species have been reported to have larger effects on SOC in forest soils than other species (Binkley, 2005). Many studies have shown that *Acacia* plantations enhance SOC more than other land uses (Table 2.4) e.g. SOC accumulation in *A. mangium* and *A. auriculiformis* plantations can be much higher than that in eucalypt plantations, mixed native stands, pine forest, grassland and abandoned land (Garay et al., 2004; Schiavo et al., 2009; Yang et al., 2009; Dong et al., 2014). Soil organic carbon is often reported to increase with successive *Acacia* rotations and this increase is associated with site preparation and litter deposition (Sang et al., 2013; Dong et al., 2014; Huong et al., 2014). Tropical *Acacia* species have high litter deposition rates, for example, 9.4 – 11.1 Mg ha^{-1} yr^{-1} for *A. mangium* (Li et al., 2000; Hardiyanto and Wicaksono, 2008), and 4.8 – 6.7 Mg ha^{-1} yr^{-1} for *A. auriculiformis* (Li et al., 2000; Huong et al., 2008). Higher litter deposition rates are expected for *A*. hybrid as it has higher growth rates than its parents (Kha, 2001; van Bueren, 2005). Biomass production of *A. mangium* plantations has been correlated to the total carbon in soil (Sang et al., 2013).

Site management using slash retention after harvesting may be key to maintaining or increasing SOC especially in short-rotation plantations (Nambiar et al., 2000; Mendham et al., 2003). Frequent cultivation of *Acacia* associated with subsequent removal of larger amounts of plant residues has been shown to result in low SOC content corresponding to a reduction in SOM inputs (Tahir et al., 2009). In other forest plantations the dissolved SOC has been shown to be dependent on both the fire intensity of inter-rotational burning and the quality/quantity of crop residues (Smith et al., 2005; Dovey and du Toit, 2006). As the silvicultural regimes for *Acacia* in Vietnam are modified to ensure sustainability and productivity, the influence of different silvicultural regimes on the amount of litter, the treatment of harvest residues such as slash retention or burning must all be considered in terms of their capacity for below-ground storage of carbon (Nambiar and Harwood, 2014).

Table 2.4 Stocks of SOC (Mg ha^{-1}) under different land uses.

Regions	Stand age (year)	Soil depth (cm)	Land use *Am*	*Aa*	*A*h	*E*	SF	P	AL	GL	References
North Vietnam	9 – 16	0 – 30	56.6			46.2	60.5	56.5			(Sang et al., 2013)
Central Vietnam	5	10 – 20			19.5				13.0		(Dong et al., 2014)
South Vietnam	5 – 7	0 – 10	48.3	27.0		44.4	51.2	52.6			(Sang et al., 2013; Huong et al., 2014)
South China	24	0 – 20	35.4	42.8						34.6	(Yang et al., 2009)
	23	0 – 10	53.6	56.8		42.0				43.9	(Wang et al., 2010)
India		0 – 15							4.76	30.0	(Saha et al., 2011)
Indonesia	7	0 – 40	69.4								(Hardiyanto and Nambiar, 2014)

Am: *A. mangium*; *Aa*: *A. auriculiformis*; *A*h: *A.* hybrid; *E*: *Eucalypts*; SF: Secondary forest; P: Pasture, AL: Abandoned land; GL: Grassland

2.6.3. Soil nitrogen

Nitrogen fixing trees in tropical environments appear to offer both high rates of growth and soil enrichment and a wide variety of N_2-fixing trees is available for use in plantations (Binkley and Giardina, 1997). Only a handful (belonging to *Paraserianthes, Casuarina, Leucaena* and *Acacia*) have received much study for silviculture and management, fewer have been examined for rates of N-fixation or effects on site fertility and nutrient cycling (Binkley and Giardina, 1997). For nitrogen fixing species, nitrogen cycling is influenced by many different factors such as silvicultural regimes including fertilisation, the quantity and quality of litter input to the soil, micro-climate, the flora and fauna in the soil (Binkley, 2005) and importantly the quantity of nitrogen fixed, the quantity of N and other nutrients taken up from the soil (Macedo et al., 2008; Kasongo et al., 2009; Yang et al., 2009). Rates of N-fixation depend on the density, age and growth of the host plants, the degree of nodulation, the genetics of the host, mycorrhizae and N_2-fixing bacteria, and environmental factors that affect plant growth (Forrester et al., 2006).

Nitrogen input rates from symbiotic N_2-fixation in plant symbioses have been estimated to be less than 1 to more than 200 kg N ha^{-1} yr^{-1}, which may be about 10% to nearly 100% of the total N used by the host plant (Forrester et al., 2006). Nitrogen fixation rates reported for *Acacia* are highly variable. In Hawaii 7-yr-old acacia stands have been reported to fix high amounts of N, around 100 to 150 kg N ha^{-1} yr^{-1} (Bernhard-Reversat, 1996; Binkley and Giardina, 1997) with fixation higher in *A. auriculiformis* than *A. mangium* (Bernhard-Reversat, 1996). In Sao Paulo, Brazil

Bouillet et al. (2008) found that at 30 months *A. mangium* fixed N at the rate of 30 – 65 kg N ha^{-1} yr^{-1}.

Studies clearly indicate that *Acacia* plantations in the tropics may increase and improve soil nitrogen content (Table 2.5). Macedo et al. (2008) found that planting N_2-fixing species (*A. auriculiformis* and *A. mangium* among others) for the recovery of tropical forests in Congo increased nitrogen stocks by 0.1 Mg ha^{-1} yr^{-1}. According to Hardiyanto and Nambiar (2014), amounts of soil nitrogen in the top 40 cm increase 4% over 12 years across successive rotations of *A. mangium* plantations in South Sumatra, Indonesia. For tropical acacias that have been managed over long rotations, TN was found to be significantly higher than in adjacent scrublands, grasslands, degraded and abandoned lands (Yamashita et al., 2008; Yang et al., 2009; Wang et al., 2010; Sang et al., 2013; Dong et al., 2014). *Acacia* planting is not always reported to increase soil nitrogen at a higher rate than other land uses e.g. Yamashita et al. (2008) stated that TN in the 0 – 20 cm soil layer was not significantly different from among 8-yr-old *A. mangium* plantation, secondary forest and *Imperata* grassland. It is especially difficult to establish the influence of different *Acacia* species on soil nitrogen unless the species are directly compared at the same site and there are conflicting reports e.g. Yang et al. (2009) reported a higher soil N for *A. mangium* than *A. auriculiformis* but the opposite result was found by (Bernhard-Reversat, 1996).

The greatest need for research in the near future is on the role of nutrient limitation in the growth of *Acacia* plantations and in sustaining soil fertility through a combination of N-fixation and fertilisation. Tropical plantations produce the greatest amount of wood per hectare of any forests and such high productivity clearly cannot be sustained after harvest of nutrient-rich biomass without specific attention to nutrition management including inter-rotational practices such as slash management. Appropriate nutrition management especially under silvicultural regimes for the production of sawlogs, such as fertilisation with P, may not only sustain or increase growth rates, it may also lead to higher rates of N-fixation and improved soil fertility as well as optimal sawlog production.

Table 2.5 Stocks of soil N (Mg ha^{-1}) under different soil depth and land uses.

Regions	Stand age (year)	Soil depth (cm)	Land use *Am*	*Aa*	*Ah*	*E*	SF	P	AL	GL	References
North Vietnam	9 – 16	0 – 10			1.0 – 1.1						(Son, 2006; Sang, 2008)
Central Vietnam		0 – 10	2.3		0.8		1.9	2.0			(Son, 2006; Sang, 2008)
	5	0 – 20			1.6				1.0		(Dong et al., 2014)
South Vietnam	5 – 7	0 – 10	1.2 – 2.4	2.0	0.6 – 2.7		1.4 – 1.9	1.3 – 1.6			(Huong et al., 2008; Sang, 2008; Huong et al., 2014)
		0 – 20			0.9						(Dung et al., 2013)
South China	24	0 – 20	2.1	2.1						1.9	(Yamashita et al., 2008; Yang et al., 2009)
	23	0 – 10	1.0	1.1		0.9				0.9	(Wang et al., 2010)
Thailand	3.5	0 – 3	0.9								(Norisada et al., 2005)
Indonesia	7	0 – 40	5.4								(Hardiyanto and Nambiar, 2014)

Am: *A. mangium*; *Aa*: *A. auriculiformis*; *A*h: *A.* hybrid; *E*: *Eucalypts*; SF: Secondary forest; P: Pasture, AL: Abandoned land; GL: Grassland

2.6.4. Soil exchangeable cations and soil acidity

Cation exchange capacity is the total capacity of a soil to hold exchangeable cations. It influences the soil's ability to hold onto essential nutrients and provides a buffer against soil acidification (Hazelton and Murphy, 2007). The main ions associated with cation exchange capacity (CEC) in soils are the exchangeable cations: calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+}) and are generally referred to as the base cations (Rayment and Higgingson, 1992). In most cases, summing the analysed base cations gives an adequate measure of CEC which is a useful indicator of soil fertility because it shows the soil's ability to supply three important plant nutrients: calcium, magnesium and potassium. Soils with a higher clay fraction tend to have higher CECs, soils with significant organic matter have very high CECs, sandy soils rely heavily on the high CEC of organic matter for the retention of nutrients in the topsoil.

Because organic acid dissociation depends on the soil pH, the CEC associated with soil organic matter is called pH-dependent CEC (CUCE, 2007; Astera, 2010). This means that the actual CEC of the soil depends on the pH of the soil (CUCE, 2007; Astera, 2010). The soil pH of Vietnamese soil ranges between 3.3 and 5.5 and as such is considered acidic regardless of land use or degradation status (Table 2.7). *Acacia* appears to tolerate a wide range of sandy to clay soils, including highly degraded soils, with pH_{KCl} values as low as 3.5, particularly in central and southern Vietnam (Que et al., 2010; Sang et al., 2013; Dong et al., 2014).

The CECs of soils in Vietnam are very low, especially for degraded land, and range from 0.3 – 0.8 (Sang et al., 2013; Dong et al., 2014). These low CECs are reflected in measurements made in *Acacia* plantations (Table 2.6) most often planted on degraded land. The CECs in Table 2.6 range from 1.08 cmol kg^{-1} for *A. mangium* plantations in North Vietnam (Sang et al., 2013) to 2.8 cmol kg^{-1} for a 5-yr-old *A.* hybrid plantation affected by erosion and leaching in Central Vietnam (Dong et al., 2014).

In weathered soils CEC can be improved by adding lime and raising the pH (Anderson et al., 2013). Otherwise, adding organic matter is the most effective way of improving the CEC (Craswell and Lefroy, 2001). In agriculture this can be done with permanent pasture, regular slashing, green manure crops, leaving crop stubbles to rot, rotating crops or pasture, and the addition of mulch and manure (Devi and Choudhury, 2013). Reforestation has been reported to improve CEC but this response to tree planting will be site specific and strongly influenced by the soil type, tree species and silviculture (Dong et al., 2014). In Brazil, a positive response in CEC to reforestation was greater under *A. mangium* than under either *E. pellita* (Dias et al., 1994) or *E. grandis* (Garay et al., 2004) possibly due to greater contribution by *A. mangium* to SOM. Dong et al. (2014) suggested that significantly higher concentrations of exchangeable cations found in second rotation *Acacia* plantations in Vietnam were in part related to cation input when burning litter and slash during land preparation. Without burning practices, different slash and litter retention treatments even over three rotations did not have any impact on CEC in *A. auriculiformis* plantations (Huong et al., 2014).

Mobility of a nutrient within the soil is closely related to the soil chemistry including CEC, as well as the soil conditions, such as moisture. When there is sufficient moisture in the soil for leaching to occur, the percolating water can carry dissolved nutrients which will be subsequently lost from the soil profile. The nutrients which are easily leached are usually those nutrients that are less strongly held by soil particles. Potassium (a monovalent cation) will leach more readily than calcium (divalent cation) since calcium is more strongly held to the soil particles than potassium (Astera, 2010). Soils with a low CEC are more prone to the leaching of cations (CUCE, 2007) than high CEC soils and to develop nutrient deficiencies.

While CEC may improve under forest plantations the differential leaching of cations in low CEC soils may influence the outcomes in terms of soil nutrient availability and pH. In *A. auriculiformis* planted on sandy soil in the Congo, the sum of exchangeable cations increased but stocks of K^+ and Na^+ did not change as much as those for Ca^{2+} and Mg^{2+} (Kasongo et al., 2009). Exchangeable Ca^{2+}, Na^+ but not K^+ increased in *A. mangium* and *A. auriculiformis* plantations in South China on degraded soils (Wang et al., 2010). Exchangeable K^+ in reforested silaceous sands in Vietnam was similar to that in the soil of abandoned land (Dong et al., 2014).

There is evidence that *Acacia* plantations increase soil acidity (Yamashita et al., 2008; Kasongo et al., 2009; Yang et al., 2009; Wang et al., 2010; Sang et al., 2013; Dong et al., 2014). For example, the soil pH of *A. mangium* plantations in four regions of Vietnam was significantly lower than in nearby secondary forest and pasture (Sang et al., 2013) and that of 5-yr-old *A.* hybrid plantations in central Vietnam was 0.2 units lower than abandoned land (Dong et al., 2014). Similar low soil pH values under *Acacia* in Vietnam are also reported under *Acacia* in other tropical countries (Yamashita et al., 2008; Yang et al., 2009; Wang et al., 2010). Yamashita et al. (2008) also compared soil under first rotation *A. mangium* plantations compared to that under secondary forest and *Imperata* grassland and found a lower soil under *A. mangium*. The reported decreases in soil pH in *Acaci*a plantations are controversial and may only be transient (Nambiar and Harwood, 2014). Results reported by Siregar et al. (2008) for *A. mangium* in Riau province, Indonesia and by Huong et al. (2008) for *A. auriculiformis* in South Vietnam show that by the end of the second rotation pH had returned to initial values. Removal of all above ground biomass at harvest may result in a decline in soil pH partly because of the concomitant potential loss of cations from the surface soil (Yamashita et al., 2008) but this is restored by litterfall over the rotation.

Table 2.6 Soil exchangeable cations (cmol kg^{-1}) under *Acacia* plantations.

Regions	Land use	Stand age (year)	Soil depth (cm)	K^+ (cmol kg^{-1})	Na^+	Ca^{2+}	Mg^{2+}	Total CEC	References
North Vietnam	*A. mangium*	9 – 16	0 – 10					0.5	(Sang et al., 2013)
	A. hybrid		0 – 10	6.8					(Son, 2006)
Central Vietnam	*A. mangium*	5 – 9	0 – 10					0.8	(Dong et al., 2014)
	A. hybrid	5	0 – 20	9.4 – 10.5	4.6	1.8	3.4		(Dong et al., 2014)
South Vietnam	*A. mangium*	5 – 7	0 – 10					0.3 – 0.7	(Sang, 2008)
	A. auriculiformis	6	0 – 10	2.0 – 0.4		9.4 – 0.3	2.4 – 0.2	14.3	(Huong et al., 2008; 2014)
	A. hybrid		0 – 20	1.7		0.5	0.7		(Son, 2006; Dung et al., 2013)
South China	*A. mangium*	24	0 – 20	0.02	0.01	0.02	0.06		(Yamashita et al., 2008; Yang et al., 2009)
	A. auriculiformis	24	0 – 20	0.02	0.01	0.02	0.005		(Yang et al., 2009)
Indonesia	*A. mangium*	7 – 8	0 – 40	6.1		175.0	4.5	4.7	(Hardiyanto and Nambiar, 2014)
Brazil	*A. mangium*	3	0 – 20	0.2	1.3	3.2	2.1	6.9	(Schiavo et al., 2009)

Am: *Acacia mangium*; *Aa*: *Acacia auriculiformis*; Ah: *Acacia* hybrid; *E*: *Eucalypt*; SF: Secondary forest; P: Pasture, AL: Abandoned land; GL: Grassland

Table 2.7 Soil pH under different land uses.

Regions	pH	Stand age (year)	Soil depth (cm)	Land use							References
				Am	Aa	Ah	E	SF	P	AL	
North Vietnam	H_2O	9 – 16	0 – 10	3.9			4.7	3.3			(Sang, 2008)
	KCl		0 – 10			3.3					(Dung et al., 2013)
Central Vietnam	H_2O	5 – 11	0 – 20	4.6		3.9		4.5	5.1	4.0	(Sang, 2008; Dong et al., 2014)
	KCl	5	0 – 20			4.2 – 4.3		4.5 – 4.7	4.5 – 4.9	4.5	(Sang, 2008; Dung et al., 2013; Dong et al., 2014)
South Vietnam	H_2O	5 – 7	0 – 20	4.3 – 4.4	4.6 – 4.8	4.0					(Huong et al., 2008; Dung et al., 2013)
	KCl	5 – 6	0 – 20		4.0	5.2					(Dung et al., 2013)
South China	H_2O	23 – 24	0 – 20	3.8 – 4.1	4.3 – 5.0						(Yamashita et al., 2008; Yang et al., 2009; Wang et al., 2010)
	KCl	24	0 – 20	4.3 – 4.2							(Yang et al., 2009)
Congo	H_2O	3	0 – 10	5.5 – 5.0							(Kasongo et al., 2009)
Indonesia	H_2O	2 – 7	0 – 40	4.1-4.6							(Siregar et al., 2008)
	KCl	7	0 – 40	3.9							(Hardiyanto and Nambiar, 2014)

Am: *Acacia mangium*; *Aa*: *Acacia auriculiformis*; Ah: *Acacia* hybrid; *E*: *Eucalypt*; SF: Secondary forest; P: Pasture, AL: Abandoned land; GL: Grassland

2.6.5. Soil physical properties

The physical properties of a soil are defined by its structure, depth, soil water characteristics and available water, texture, colour, consistency, porosity, density and water flows (FAO, 2006). Although soil properties are conveniently classified into physical, chemical and biological classes there is much interaction between the three which influences the soil properties already discussed in this literature review i.e. soil carbon, soil nitrogen, CEC and pH (FAO, 2006). Soils evolve under the action of biological, climatic, geologic and topographic influences. There are five fundamental soil formation processes that influence soil properties: parent material, topography, climate, time and organisms (Soil Survey Staff, 2006). However, living organisms such as vegetation also have an important role in a number of processes involved in soil formation including organic matter accumulation, profile mixing and biogeochemical nutrient cycling (Nsalambi and Christopher, 2010). Litterfall and vegetation decomposition, add humus and nutrients to the soil which influences soil structure and fertility (Soil Survey Staff - NRCS, 2007). Soil water holding capacity is affected by soil texture and structure, soil capillarity, porosity and soil organic matter (Landsberg and Sands, 2010). Although inferences can be made from the literature about the effect of vegetation type on soil physical properties (e.g Nsalambi and Christopher, 2010), there is very little in the literature about the specific influence of *Acacia* plantations on soil physical properties.

Several studies found that bulk density in *Acacia* plantations is significantly lower than abandoned land, open site and annual monoculture cropping systems (Tahir et al., 2009; Yang et al., 2009; Dong et al., 2014) and was attributed to a higher amount of leaf litter fall and higher rate of its decomposition under plantations (Dong et al., 2014). Tahir et al. (2009) investigated the changes in soil physical properties before and after conversion of a 6-yr-old *Acacia senegal* plantation to other land management systems (e.g. pure and intercropped systems) showed that fine sand, clay and silt content increased while coarse sand content decreased under plantations. The result was explained by reduced soil erosion due to surface litter and also stabilisation of aggregates due to the presence of higher organic matter in plantations (Tahir et al., 2009). In agroforestry systems tree crowns and their litter cover reduce wind and water erosion and improve soil physical properties (Buresh and Tian, 1998; Tahir et al., 2009).

Available soil water is critical for determining growth rates that maintain physiologically active foliage during prolonged periods of drought in tropical plantations (Binkley and Giardina, 1997; Tiarks et al., 1998). Bin et al. (2007) related improved soil infiltration and water storage capacity in older *A. mangium* due to reduced bulk density and increased SOM. Yang et al. (2009) have also reported improved soil water holding capacity under *A. mangium* compared to both *A. auriculiformis* and a barren site (Yang et al., 2009).

2.7. Sustainability of *Acacia* plantations

2.7.1. Effects of site management on soils and plantation growth

Attention has been drawn by several authors to the capacity as well as risks of the humid tropical ecosystems to sustainably support fast growing plantation species and to cope with the potential impacts of loss of organic matter and nutrients through successive harvests (Folster and Khanna, 1997; Harwood and Nambiar, 2014a; Huong, 2016).

As described in Section 2.6 of this literature review *Acacia* plantations established on degraded lands in Vietnam appear to have the potential to conserve and even increase some key soil chemical and physical properties to plant growth such as SOC and TN (Anh et al., 2014; Dong et al., 2014; Hung et al., 2016a), but there is concern that soil acidification may occur in *Acacia* plantations due to the removal of biomass and nutrients during harvest (Sang et al., 2013; Dong et al., 2014; Hung et al., 2016a). Not all authors agree with the latter observations and Hardiyanto and Nambiar (2014) have shown that SOC and pH remained unchanged over successive short rotations of *Acacia* in Indonesia. There is a paucity of well designed and long term experiment to allow definitive conclusions about the sustainability of *Acacia* plantations. There are however some indications as to how management practices might influence sustainability and promote some of the more positive benefits of *Acacia* plantations. Several studies have shown that the inter-rotation site management such as wood harvest, biomass removal and site preparation can have significant effects on productivity of successive rotations of *Acacia* plantations (Hardiyanto and Nambiar, 2014; Huong et al., 2014; Nambiar and Harwood, 2014).

Across Vietnam, clear-fall cutting and burning slash and litter after harvesting continues to be commonly practiced to reduce associated costs including labour (Dong et al., 2014; Huong et al., 2014). These practices can lead to substantial losses of SOM and nutrients due to increased erosion and leaching, particularly during the wet season (Paul et al., 2002; Macedo et al., 2008). Wood harvesting of biomass can cause considerable depletion of nutrients – one study showed removal of available P (4.4 kg ha^{-1}), K (115.8 kg ha^{-1}) and Ca (49.2 kg ha^{-1}) in *A. auriculiformis* plantations in Southern Vietnam (Huong et al., 2008) while a second study reported removal of available P (7.8 – 12.2 kg ha^{-1}), K (73 – 91 kg ha^{-1}), Ca (267 – 357 kg ha^{-1}) and N (264 – 371 kg ha^{-1}) in *A. mangium* plantations in South Sumatra, Indonesia (Hardiyanto and Wicaksono, 2008).

There is good evidence that soil fertility generally increases after second rotation when slash and litter is retained between successive rotations. The *MAI* of *A. mangium* plantations over 12 years successive rotations in South Sumatra, Indonesia, increased from 29.4 m^3 ha^{-1} yr^{-1} in the first rotation to 43.0 m^3 ha^{-1} yr^{-1} in the second rotation resulted in retention of biomass from the previous rotation (Hardiyanto and Nambiar, 2014). This study found that whole tree harvesting (full stem with wood, all branches and leaves) resulted in a 17% reduction in volume in the next rotation compared to harvesting stem merchantable wood alone. Similarly, the increases in productivity of *A. auriculiformis* plantations from 10.6 m^3 ha^{-1} yr^{-1} in the first rotation (age 7 years) to 28.3 m^3 ha^{-1} yr^{-1} in the second rotation (age 6 years) and to 33.9 m^3 ha^{-1} yr^{-1} at age 5 years in the third rotation in South Vietnam were observed over three successive rotations covering 15 years through residual litter management after harvesting (Huong et al., 2014).

On the flat slopes of South Vietnam, site preparation also involves ploughing the site, up to three times (Nambiar et al., 2015). Nambiar and Harwood (2014) state that there is a serious need to critically examine the impacts of intensive tillage such as repeated ploughing on SOM, nutrient pools and soil physical properties in plantations in some parts of SE Asia including Vietnam.

Better understanding of the context in which tropical plantation interacts with soil moisture will inform a range of production and environmental decisions for sustainability, including those for the restoration of degraded landscapes (Russel et al., 2007; Dell et al., 2012). Few studies have investigated the interaction between high water tables, soil moisture, and tree specific water use in tropical plantation. Miyazawa et al. (2014) reported that in central Cambodia, in which 90% of annual rainfall (1700 – 1800 mm yr^{-1}) falls over a seven month period, the transpiration characteristics of three tropical species (*Shorea roxburghii, E. camaldulensis, Dipterocarpus obtusifolius*) was more closely related to seasonal groundwater dynamics than rainfall patterns. Differences in soil water extraction between plantation species is thought to be less important than tree size in many situation (Meinzer et al., 2004; Meinzer et al., 2005; Kunert et al., 2010), although differences in soil moisture, sap flux or transpiration have been noted between species of similar sized trees. Very few studies relating to water use have been carried out for *Acacia* plantation species although Mendham et al. (2015) describe some preliminary experiments to investigate the interactions between site edaphic properties, soil fertility, slope, water availability and effects of management on productivity in Sumatra, Indonesia.

2.7.2. Carbon sequestration of Acacia plantations

One important ecological value of plantations is their capacity to sequester carbon, first by storing carbon dioxide fixed in photosynthesis in above- and below-ground biomass in the short- to medium- term (during 5-to-10 years rotations), and second by transferring some of this carbon to soil in the medium- to long-term (over decades and possibly much longer) (Sang et al., 2013). While evaluations of biomass production, carbon sequestration, soil improvement and other ecological services in temperate plantation systems have been well quantified (Bernhard-Reversat, 1996; Binkley and Giardina, 1997; Binkley, 2005), few such studies have been undertaken in tropical plantations (Sang et al., 2013).

In addition to supplying the demand for wood and wood products, forest plantations of Vietnam have recently been recognised for their potential role to influence national carbon budgets and CO_2 mitigation (Sang et al., 2013). To meet this goal in Vietnam, one challenge is to increase the quantity and improve the quality and value of wood from existing and future planted forests. Substantial areas of degraded land still remain that can be restored to provide wood products and ecological services (Phuong, 2007, 2011; IPCC, 2014). Incorporating wood production and carbon sequestration by plantations may bring significant benefit for these development forest projects, contributing not only to meet wood demands but to also provide ecological services including biodiversity and restoration of soil fertility services (Phuong, 2011; IPCC, 2014).

The potential role of plantations in carbon sequestration was first recognised in 2004 in Vietnam (Phuong, 2011). Since then, carbon sequestration studies have been published for *Acacia*, *Eucalyptus* and *Pinu*s species in Vietnam (Phuong, 2007, 2011). As expected carbon sequestration is dependent on many factors; species, silvicultural regime and site. Values of carbon range considerably e.g.

- 60 – 407 tonnes C ha^{-1} for 2-3-yr-old *A.* hybrid plantations (800 – 1350 trees ha^{-1})
- 66 – 292 tonnes C ha^{-1} for 5-12-yr-old *A. auriculiformis* (1033 – 1517 trees ha^{-1})
- 18 – 469 tonnes C ha^{-1} for pine at age 5 – 21 years
- 107 – 378 tonnes C ha^{-1} for *E. urophylla* at age 3 – 12 years (1200 – 1800 trees ha^{-1}).

Trade-offs between carbon sequestration and economic values need careful negotiation and depend on national and international policy decisions to encourage investment (Sang, 2008). Therefore, the potential role of *Acacia* plantations in carbon sequestration remains unclear in Vietnam. The high rate of carbon fixation of Acacia will need to be offset against their comparatively short life span, so plantings would need to be in the context of a sustainably harvested system (Griffin et al., 2011).

2.8. Productivity modelling in forestry

2.8.1. Importance of modelling forest growth

In terms of sustainable forest management, measuring site quality and predicting site productivity remains a major forestry topic (Jean-Daniel and Olivier, 2014). Forest managers need to be able to predict how forests will respond to natural conditions or to changes caused by management actions designed to achieve specified results in the future (Almeida et al., 2010a). Plantation growth is traditionally predicted at tree and stand scales using empirical models which use data from forest inventory measurements (Vanclay, 1998). Regressions are developed to predict annual growth rates from input variables including tree/stand age, size and stocking, soil properties and critical climate variables such as annual rainfall (Almeida et al., 2007). These empirical or statistical growth models can predict, with good accuracy, growth at the sites and under the environmental conditions for which they have been developed. However, their reliable application is limited to the land base, range of environmental conditions and genetic material for which the data were collected (Landsberg and Sands, 2010).

Table 2.8 Relative differences in the characteristics of process-based and empirical modelling approaches (Taken from Adams et al. (2013)).

	Process-based	**Empirical**
Relationship type	Causal	Correlative
Relative comprehensiveness	More comprehensive	Less comprehensive
Incorporation of mechanism	Explicit	Implicit
Primary source of error	Unknown parameters and processes	Extrapolation
Model uncertainty	Higher	Lower
Data requirements	Higher	Lower
Spatial scale for calibration	Smaller	Smaller to larger
Spatial scaling of prediction	Smaller to Larger	Best at scale of calibration

Apart from the traditional statistical models of site productivity, process-based models (PBMs) have been discussed as a potential tool for forest management, in spite of serious limitations (Korzukhin et al., 1996; Battaglia and Sands, 1998b; Mäkelä et al., 2000; Luckai and Larocque, 2002). Process-based models are designed to predict yields from the simulation of plant functioning according to endogenous plant properties and environmental conditions (Landsberg and Sands, 2010). Simplified PBMs have emerged as a means to predict site productivity over large regions (Zhou et al., 2005; Coops et al., 2010), using spatialized and satellite-based environmental information.

The advantages and disadvantages of both empirical and PBMs have been well described and are discussed by Adams et al. (2013) in the context of predicting forest mortality in response to climate-change induced drought, increased temperatures, and infestation of tree pests. In process-based model outputs uncertainty is higher than for the empirical approach due to greater model parameters and data inputs to represent the many processes in the system (See Table 2.8). In the empirical approach, model uncertainty may be reduced, yet significant bias can result from exclusion of important system components by extrapolation of correlative relationships beyond observed variability. Process-based models can however better include responses which may occur with future conditions but are not well quantified in past observations. Realistically, many models use a hybrid approach, combining process-based and empirical representation of relationships. Adams et al. (2013) suggest an ensemble approach for forest mortality should include models from across the spectrum of empirical to process-based types.

2.8.2. Application of 3-PG model in predicting productivity

The process-based model Physiological Processes Predicting Growth (3-PG) (Landsberg and Waring, 1997) is a practical tool for examining productivity differences in relation to environmental variables and to evaluate impacts of management practices

(Almeida et al., 2004a). According to Almeida et al. (2004a), the main areas of application of 3-PG in the decision making process and operation activities are: estimation of potential productivity, forest growth analyses, effects of climate variability and strategic scenarios. A detailed description and application of the model is given by Landsberg and Sands (2010). This tool has been used to predict stand growth and biomass production over a wide range of geographical locations with different climates, soils, tree species and management regimes but mainly for temperate forests (Landsberg and Waring, 1997; Sands and Landsberg, 2002; Landsberg et al., 2003; Almeida et al., 2004b; 2004a; Dye et al., 2004; Nightingale et al., 2008b; 2008a). The application of 3-PG to tropical forests and a tropical tree species such as an *Acacia* remains limited (Morris et al., 2004; Hua et al., 2007; Sang, 2008).

The main outputs of the model are related to biomass and water balance (Almeida et al., 2004b; Almeida et al., 2007). They include stem, root and foliage biomass, diameter at breast height, stand volume, mean annual increment, current annual (or monthly) increment, stem number, leaf area index and components of the water balance including available soil water, stand transpiration and evapotranspiration, canopy interception and runoff. Sands (2004) described the sequence of steps required to parameterise 3-PG. The basic data required to calibrate the 3-PG model are location (latitude), climate, site characteristics including site fertility rating, maximum available soil water and soil texture and species characteristics. Information about forest management, such as planting date, stocking and any thinning schedules, are also part of the input data.

Booth et al. (2001) was the first to apply 3PG to *Acacia* plantations in Vietnam. The model was parameterised and calibrated for *A. mangium* using limited experimental data obtained from commercial plantations. The study found that model predictions of *MAI* over the 32 sites studied were accurate for plantations in each of five soil types and highlighted, at least for *A. mangium* plantations, how sensitive modelled predictions are to height and stand stem volume allometric equations. Almeida et al. (2014) subsequently mapped the productivity potential of *A. mangium* plantations in Vietnam under different climate change scenarios using 3PG. The predicted impacts of future climates on productivity were highly variable across regions as might be expected for the different environments of Vietnam but could also be linked to the parameterisation of the model.

The problem with 3-PG, in many cases, is to obtain the appropriate parameter values for the functional relationships between processes and the variables that drive those (Almeida et al., 2004a; Hung et al., 2016b). Several reviews have proposed the estimation of fertility rating based in part on soil properties and silvicultural treatments (Stape et al., 2004; Fontes et al., 2006; Vega-Nieva et al., 2014); and in part on expert knowledge of growth on similar sites, or of previous crops or stands on the sites (Esprey et al., 2004; Landsberg and Sands, 2010); indirect estimation from site index (Dye et al., 2004; Gonzalez-Benecke et al., 2014); best match between model predictions and the measured average stem diameter and aboveground biomass from each stand (Landsberg et al., 2001; Sampson et al., 2006; Bryars et al., 2013); or a general empirical expression to include factors such as waterlogging or topography limitation (Almeida et al., 2010a). In general, many attempts proposed for the estimation of fertility rating have been assigned, mainly for eucalypt and pine species, but no studies have focussed on *Acacia* species using a long-term dataset from controlled experiments in a wide range of conditions.

2.9. Summary

The review has shown that *Acacia* plantations in Vietnam continue to be a vitally important resource of wood for a range of uses. The growth of Vietnam's substantial pulp and paper industries and increasing domestic demand for sawlog products need to be underpinned by a large area of sustainably grown local plantations. Tree genetics and breeding research has been in progress for nearly three decades, that on site and stand management for over a decade. Recently, the productivity of *Acacia* plantations in successive rotations has been decreasing. Studies to understand the decline in yields and to ensure the sustainable management of *Acacia* plantations are in progress.

Selected *Acacia* species including *A. mangium*, *A. auriculiformis* and their hybrid are tolerant of a variety of poor acidic and leached soils and as nitrogen-fixing species have the potential to improve soil properties. Although soil properties for a range of *Acacia* plantation sites in Vietnam have been summarised and reported by several authors, there is still very limited information available that examines the effects of land use on soil properties.

There are strong regional differences in the growth rates of *A.* hybrid across Vietnam. Attempts to explain these differences in productivity have highlighted the potential effects on growth of many variables such as genotype, site quality, stand management and environment variables. However, there is very limited information available that adequately quantifies how much soil and environmental variables affect productivity. Given the strong variability in regional productivity, there is a need to find tools that can accurately predict the potential productivity of *Acacia* plantations at regional levels. Process based models such as 3-PG, provide a powerful systems approach for examining productivity differences in relation to climate variables, soil types, water use, nutrient supply and to evaluate options for silvicultural management in Vietnam.

CHAPTER 3

PREDICTING PRODUCTIVITY OF *ACACIA* HYBRID PLANTATION FOR A RANGE OF CLIMATES AND SOILS IN VIETNAM

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CHAPTER 3. PREDICTING PRODUCTIVITY OF *ACACIA* HYBRID PLANTATION FOR A RANGE OF CLIMATES AND SOILS IN VIETNAM

Abstract

Acacia hybrid (*A. auriculiformis* × *A. mangium*) has rapidly become the most widely planted species in Vietnam for the production of pulpwood and sawlogs. As it is adapted to the very wide range of site and soil conditions that prevail throughout the country, providing an ability to predict accurately its productivity is an essential part of optimising product value and income to growers. In this study, we calibrated the 3-PG growth model using ten permanent sample plots located in stands aged 1, 3 and 6 years. The model was then validated using 55 additional permanent plots from 12 plantations growing in four regions that support plantation forestry. The model performed well for most of the validation sites; model efficiencies (*EF*) were ⩾0.76. The model was more accurate in predicting the productivity of plantations in the North and North Central Coast than in the South and South Central Coast regions. Growth was most affected by soil water deficit in this wet/dry tropical environment, than by temperature, particularly in the North. Soil fertility was best predicted by a relationship with soil organic carbon and the base cations Ca^{2+} and K^{+}. Across regions, the mean current monthly increment of stand volume for a 15-yr rotation was 3.21 and 1.97 m^3 ha^{-1} $month^{-1}$ for the wet and dry seasons, respectively. Sensitivity analysis indicated how much the model parameters affect the main outputs and how this changes with stand age. Overall, the model provided an accurate description of the potential productivity of *Acacia* hybrid plantations across a wide range of climates and soils in Vietnam.

Keywords: *Acacia* hybrid production, process-based model, variable productivity, growth limitations, sensitivity analysis

3.1. Introduction

Plantations in Vietnam are fast becoming the primary sources of wood for a range of uses; however uncertainties remain about the sustainability of their productivity (Almeida et al., 2014; Nambiar et al., 2015). This is in part because of the wide range of contrasting environments and soils in Vietnam (Hai et al., 2008a; Kha et al., 2012) that constrain productivity through a combination of variable rainfall and extended periods of drought, low winter and possibly high summer temperatures, and differences in soil fertility (Nghia, 1996; Hai et al., 2008a; Kha et al., 2012). To accurately quantify potential productivity across large plantation estates and examine the constraints and drivers to their growth, adequate models that are mechanistically robust are required (Almeida et al., 2010a).

The Vietnamese government's 2010 – 2020 strategy for forestry development targets an increase in forest cover from 39 to 45% across Vietnam (MARD, 2010; VNFOREST, 2014). Part of this initiative seeks to ensure a supply of wood and locally-manufactured wood products that can satisfy both domestic demand and supply to international markets. If successful, a total of 8.4Mha of production forests (4.15 Mha plantations, 3.63 Mha natural forests and 0.62 Mha naturally rehabilitated forest associated with agroforestry) will generate 20 – 24 M m^3 yr^{-1} of wood comprising 40% sawn timber and 60% pulpwood (MARD, 2010; VNFOREST, 2014).

A key species planted throughout Vietnam is a natural hybrid between *Acacia mangium* × *Acacia auriculiformis*, commonly referred to as *Acacia* hybrid (Kha, 2001). Growth rates for *A.* hybrid in Vietnam are highly variable with mean annual increment

(*MAI*) typically ranging between 10 – 25 m^3 ha^{-1} yr^{-1} (Nghia and Kha, 1998). Based on an examination of 30 commercial plantations, Harwood and Nambiar (2014b) noted that mean *MAI* was lower in the north than south, 17.6 *vs*. 23.0 m^3 ha^{-1} yr^{-1}, and lowest in central Vietnam, 11 m^3 ha^{-1} yr^{-1}, though much higher levels of *MAI*, 20.0 – 28.7 m^3 ha^{-1} yr^{-1} have been reported for *A*. hybrid plantations in Hue province, also in central Vietnam (Dong et al., 2014), indicating that there is potential to improve productivity within regions. The use of process-based models (PBMs) enables the prediction of potential productivities.

The PBM 3-PG is based on the physiological principles that underpin forest growth (Landsberg and Waring, 1997) and used to examine productivity differences in relation to environment and management (Almeida et al., 2010a; Landsberg and Sands, 2010; González-García et al., 2016). In Vietnam, 3-PG was first applied to quantify the potential benefits of planted forest (Booth et al., 2000), and first parameterised and calibrated for an acacia species (*A. mangium*) using limited experimental data obtained from commercial plantations (Sang, 2008). The productivity potential of *A. mangium* plantations in Vietnam under different climate-change scenarios has also been mapped (Almeida et al., 2014). However, 3-PG has yet to be parameterised and validated to quantify the effects of regional differences in climate and soil fertility on acacia productivity.

Climates in Vietnam are associated with distinct dry seasons that can constrain the growth of planted forests (Nghia, 1996). However, for acacia plantations, it is not sufficient to define suitable growing environments by mean annual rainfall alone; the length and severity of the dry season, indicated by mean monthly rainfall and pan evaporation, and soil-water storage capacity must also be considered (Harwood, 2011). 3-PG uses the concept of conversion of absorbed photosynthetically active radiation (*APAR*) to net primary production. Maximum conversion of *APAR* is reduced using growth modifiers (*f*) that represent the effects of growth constraints: available soil water (f_{ASW}), vapour pressure deficit (f_{VPD}), temperature (f_T), frost (f_F) and soil fertility (f_{FR}); these vary from zero (representing total limitation) to one (no limitation) (Landsberg and Sands, 2010). Quantifying and analysing the relativities of these modifiers can provide an understanding of constraints on growth, and advise management strategies for sustaining productivity (Almeida et al., 2010a; González-García et al., 2016). The soil fertility rating (*FR*) is an important variable in 3-PG that affects model outputs but is difficult to calculate and can involve an element of subjectivity in its determination (Esprey et al., 2004; Almeida et al., 2010a; Landsberg and Sands, 2010). Despite efforts to develop a consistent method for estimating *FR* (Stape et al., 2004; Fontes et al., 2006; Almeida et al., 2010a; Vega-Nieva et al., 2014; González-García et al., 2016), this has not included acacia plantations growing under a wide range of conditions of soil fertility. According to Almeida et al. (2004a), lack of knowledge of the effects of soil fertility on forest productivity will inevitably affect the quality of decision-making processes based on model outputs, both for wood production and ecosystem integrity. Concerns have been expressed previously about the subjectivity in *FR* estimates (Fontes et al., 2006; Paul et al., 2007; Vega-Nieva et al., 2014). This paper develops an empirical expression to calculate *FR* for the study regions in Vietnam based primarily on soil chemical properties, though an adjustment is still necessary.

The aim of this paper was to predict *A*. hybrid growth across Vietnam applying the 3-PG process-based model, and to identify and quantify the factors affecting the productivity of these plantations. The results will assist forest managers and growers to understand the capacity of these landscapes to produce wood, but at the same time to minimise risk and optimise economic and environmental outcomes for this increasingly important species.

3.2. Materials and methods

3.2.1. Inputs and outputs of 3-PG

The main input data in 3-PG are site-specific factors: latitude; maximum available soil water (ASW_{max}, mm); soil texture; *FR*; initial stocking (trees ha^{-1}); mean monthly variables: air temperature (T, °C), daily solar radiation (RA, MJ m^{-2} day^{-1}), rainfall (R, mm month^{-1}), frost days (dF, days month^{-1}); vapour pressure deficit (VPD, mb); stand initialisation as the year and month planted and age when the simulation starts; stem (stem wood + bark + branches) (W_{stem}), foliage (W_{foliar}), root (W_{root}) biomass, stocking (trees ha^{-1}), rotation length, and species-specific parameters which were developed in the study (Appendix 3.1).

The model can be run for any number of years using either actual monthly weather data or long-term monthly averages; the latter has been more common unless there is particular interest in specific events, such as drought (Sands and Landsberg, 2002). Almeida et al. (2004a) however demonstrated that using actual meteorological data is more realistic as using average data can result in the model overestimating stand volume by 25%; actual weather data were used in this study.

The outputs from 3-PG can be estimated monthly or annually. In this study, the outputs were: W_{stem}, W_{foliar}, W_{root}, and total biomass (*TW*), gross primary productivity (*GPP*), and net primary productivity (*NPP*) (all in Mg ha^{-1}), leaf area index (*LAI*, m^2 m^{-2}), stand volume (*SV*, m^3 ha^{-1}), stem number (*N*, trees ha^{-1}), average stem diameter at breast height (*DBH*, cm), basal area (*BA*, m^2 ha^{-1}), *MAI* (m^3 ha^{-1} yr^{-1}), water-use efficiency (*WUE*, gDM mm^{-1}) and evapotranspiration (*ET*, mm month^{-1}).

3.2.2. Site descriptions

The 3-PG model was parameterised and calibrated using three adjacent experimental stands of *A.* hybrid aged 1, 3 and 6 years; these are hereafter referred to as CN1, CN2 and CN3, respectively (Figure 3.1). They were located in the Ba Vi district of Hanoi city in northern Vietnam (lat. 21.1°N, long. 105.4°E) (Figure 3.1). Each is on sloping land (⩽15°) that consists of shallow (*ca* 50 cm) laterised (deeply weathered) Ferralic Acrisol soils of low fertility which are acidic and leached. Mean total annual rainfall is 1630 mm (2006 – 2014) (Table 3.1), mean monthly annual rainfall is 152 mm (1970 – 2005) and 136 mm (2006 – 2014) with a three-month dry season from December to February (Figure 3.2a); the mean monthly temperature maximum is 28.8 °C, the minimum is 20.7 °C, and mean monthly temperature is 24.7 °C (Table 3.1). In the 1960s, the area was covered by broad-leaved evergreen forest, which subsequently became degraded due to over-exploitation and shifting “slash and burn” cultivation. Since the 1990s, the land use has been short-rotation plantation forestry (Kha, 2001). The CN1, CN2 and CN3 stands were established in 2011, 2009 and 2006 respectively. In CN1 and CN2, a mixture of clones BV10, BV16 and BV32 at 3 × 3 m spacing were planted; in CN3 a mixture of clones BV10, BV16, BV32, BV33, BV71, BV73 and BV75 at 3 × 2 m spacing were planted.

Each experiment had a randomized complete block design with three replicates, each with six plots to accommodate a combination of three post-planting fertiliser and two thinning treatments. The gross plot size of CN1 and CN2 was 24 × 24 m (8 × 8 trees) and measured plot size was 18 × 18 m (6 × 6 trees); in CN3, these were respectively 24 × 18 m (8 × 9 trees) and 18 × 14 m (6 × 7 trees). All received fertiliser at planting (see below). However, for calibrating 3-PG, only control plots that received no post-planting fertiliser or thinning were used.

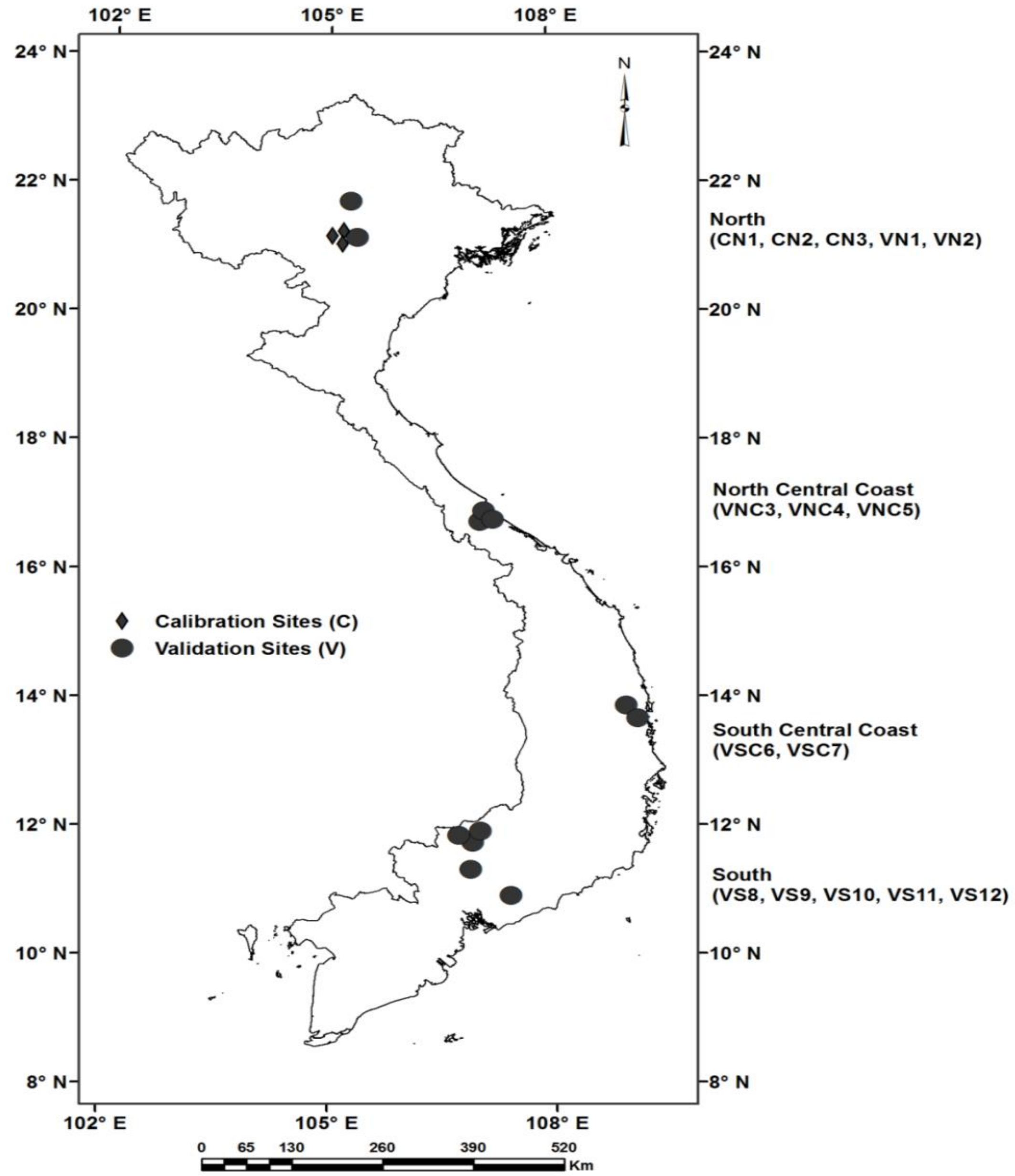

Figure 3.1 Location of the study sites.

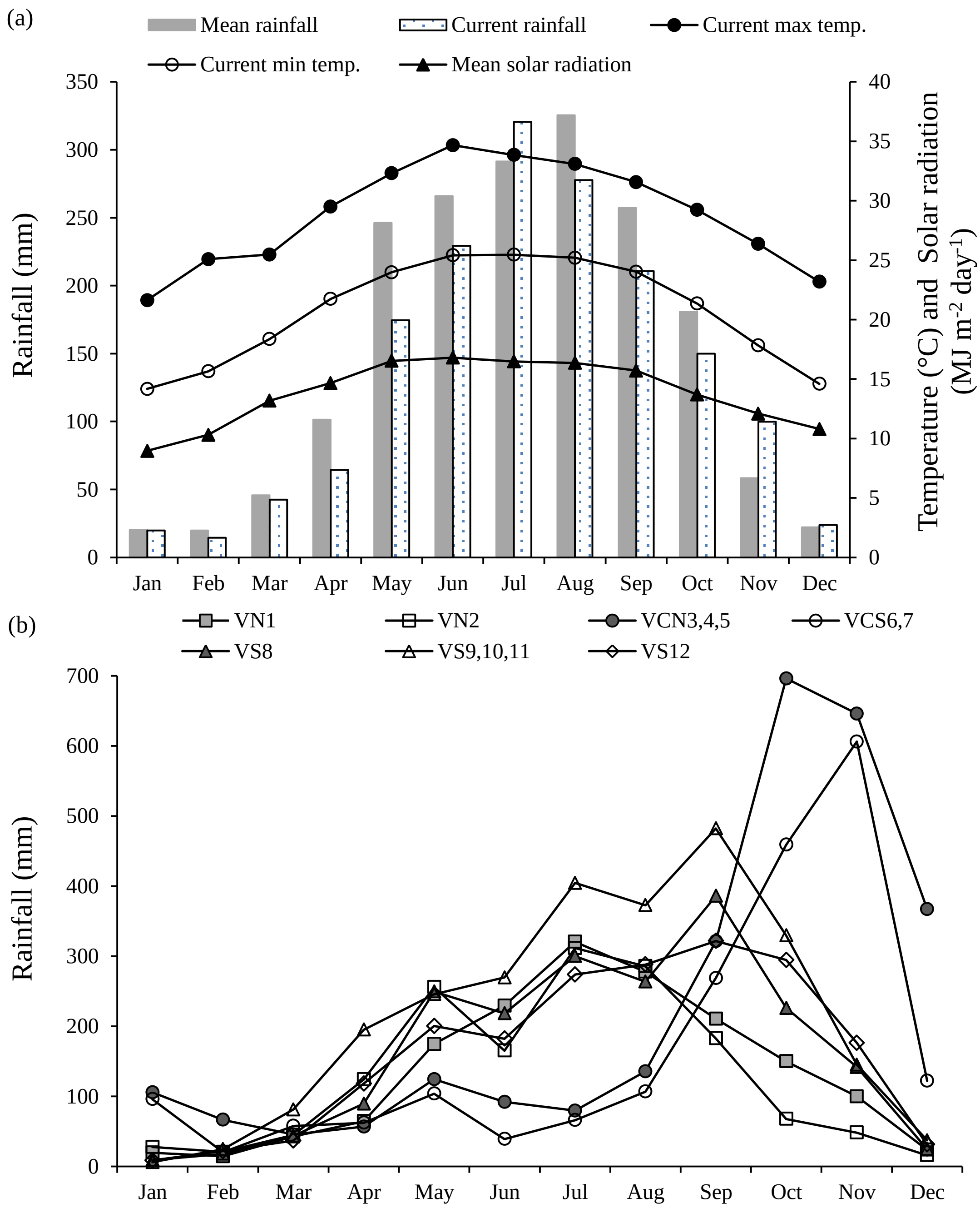

Figure 3.2 Comparison of (a) mean monthly rainfall between 1970 – 2014 and current monthly rainfall, mean minimum and maximum monthly temperatures and monthly mean daily solar radiation during the measurement period (2006 – 2014) at the Ba Vi calibration site, and (b) current mean monthly rainfall at the twelve validation sites during the measurement period (2006 – 2014).

Twelve other sites located across seven provinces in four ecological zones out of a total of eight forestry ecological zones in Vietnam (Phuong et al., 2012) and at latitudes ranging from 21.1°N to 10.8°N were used for model validation (Table 3.1). These sites represent most of the soils, topographies and climates under which *A.* hybrid is planted in Vietnam. Two sites were in northern Vietnam (VN1, VN2), three in the north central coast (VNC3, VNC4, and VNC5), two in the south central coast (VSC6 and VSC7), and five in southern Vietnam (VS8, VS9, VS10, VS11, and VS12). The climate across these sites is tropical, but differs with latitude and altitude because of a varying monsoonal regime and terrain (Lap, 1999). The VN sites have four distinct seasons. The summer is hot and rainy and affected by the north-west monsoon, and the winter is cold and dry; the mean monthly maximum temperature is 28 – 28.8 °C, the minimum is 16 – 20.7 °C and the mean annual rainfall, concentrated between May and September, is 1630 – 1650 mm (Table 3.1). At VN1 (Figure 3.2a), the monthly maximum temperature varies between 20.6 – 33.6 °C, the minimum between 14.2 – 25.5 °C, and the monthly rainfall between 19.7 – 325.6 mm; for VN2 monthly rainfall varies between 16.0 – 311.7 mm (Figure 3.2b). The VNC and VSC sites have two seasons – the hot south-west monsoon in the dry season and high frequency tropical typhoons in the wet season. The highest mean monthly temperature is 31 °C, the lowest is 22.1 °C, and the mean annual rainfall concentrated between late August to November is 1664 – 2730 mm; monthly rainfall is: VNC3, VNC4 and VNC5 (31.1 – 837.2 mm); VSC6 and VSC7 (20.6 – 606.3 mm) (Figure 3.2b). The VS sites have distinct dry and wet seasons, the latter receiving > 90% of the total annual rainfall of 1180 – 2140 mm; the mean annual temperature is 27.6 – 28.6 °C with little monthly variation; monthly rainfall is: VS8 (9.2 – 386.1); VS9, VS10 and VS11 (6.1 – 482.3 mm); VS12 (8.7 – 321.8 mm) (Figure 3.2b). Dry season in this study is defined as the number of consecutive months receiving $\leqslant$40 mm mean monthly rainfall: 3 – 4 months in VN, 2 – 3 months in VNC; 3 – 4 months in VSC; and 3 – 5 months in VS. The soils in VN were Ferralic Acrisols, in VNC and VSC were Rhodic Ferrasols and Haplic Acrisols (iron oxide rich clayey soils), respectively and in VS were Gleyic, Ferralic and Chromic Acrisols (acidic texture-contrast soils) (Table 3.2). As for the calibration sites, the validation sites were part of randomised block experiments, but only control plots that received no post-planting fertiliser or thinning were used.

Both calibration and validation sites received basal N:P:K fertiliser at planting and/or superphosphate; for P, inputs ranged from 0.01 to 0.556 kg P per tree (Table 3.1). CN3 and VN1 also received 2 kg of cattle manure per tree. At all sites, weed control was carried out at least twice per year during the first two years after planting. More detailed descriptions of the sites are provided by Beadle et al. (2013a) and Dung et al. (2013).

Table 3.1 Description of the calibration and validation study sites.

Location	Site	Lat.	Long.	Alt.	T_{max}	T_{min}	Temp.	Rainfall	Radiation	Dry month	Stocking	Planting year	Fertiliser at planting	No. of clones	Plot size
		(N)	(E)	(m a.s.l)	(°C)	(°C)	(°C)	(mm)	(MJ m^{-2} day^{-1})	month	(trees ha^{-1})	(year)	(kg per tree)		(m^2)
North	CN1[a]	21.1	105.3	35	28.8	20.7	24.7	1630	15.5	3	1111	2011	0.016 N, 0.045 P, 0.008 K	3	324
	CN2[a]	21.1	105.3	35	28.8	20.7	24.7	1630	15.5	3	1111	2009	0.016 N, 0.045 P, 0.008 K	3	324
	CN3[a]	21.1	105.3	35	28.8	20.7	24.7	1630	15.5	3	1667	2006	0.005 N, 0.01 P, 0.003 K, 2M[g]	7	432
	VN1[b]	21.1	105.3	34	28.8	20.7	24.7	1630	15.5	3	1667	2006	0.005 N, 0.02 P, 0.003 K, 2M[g]	5	432
	VN2[b]	21.7	105.2	34	28.0	16.0	22.0	1650	14.3	4	1111	2009	0.016 N, 0.045 P, 0.008 K	5	324
North Central Coast	VNC3[c]	16.8	107.0	50	29.5	22.1	25.8	2370	15.0	2 – 3	1111	2009	0.016 N, 0.045 P, 0.008 K	3	324
	VNC4[c]	16.8	107.1	30	29.5	22.1	25.8	2370	15.0	2 – 3	1333	2008	0.2 P	3	420
	VNC5[c]	16.7	106.9	37	29.5	22.1	25.8	2370	15.0	2 – 3	1333	2009	0.556 P	3	270
South Central Coast	VSC6[d]	13.8	108.9	106	31.0	24.8	27.9	1664	18.0	3 – 4	1667	2009	0.556 P	4	405
	VSC7[d]	13.8	108.9	251	31.0	24.8	27.9	1664	18.0	3 – 4	1667	2009	0.556 P	4	405
South	VS8[e]	11.3	106.8	100	33.0	22.6	27.8	2140	18.9	5	1111	2008	0.016 N, 0.045 P, 0.008 K	4	385
	VS9[e]	11.6	106.8	104	31.0	24.8	27.9	1664	18.0	3	1111	2008	0.016 N, 0.045 P, 0.008 K	4	324
	VS10[e]	11.7	107.1	273	31.0	24.8	27.9	1664	18.0	3	1143	2008	0.016 N, 0.045 P, 0.008 K	4	324
	VS11[e]	10.8	107.2	202	33.2	24.7	28.6	1600	18.3	3	1111	2010	0.016 N, 0.045 P, 0.008 K	4	324
	VS12[e]	10.9	107.4	114	31.4	23.7	27.6	1180	18.3	4	1111	2010	0.016 N, 0.045 P, 0.008 K	4	324

[a]Calibration sites comprising of three stands (CN); Weather data collected from Lang station located 5 km NW from the experimental site.
[b]Validation sites in Northern Vietnam (VN); Weather data collected from Tuyen Quang station located 10 km NW from the experimental site.
[c]Validation sites in North Central Vietnam (VNC); Weather data collected from Dong Ha station located 16 km SE from the experimental site.
[d]Validation sites in South Central Vietnam (VSC); Weather data collected from Binh Dinh station located 27 km S from the experimental site.
[e]Validation sites in Southern Vietnam (VS); Weather data collected from Dong Phu station located 27 km S from the experimental site.
[f]Calculated based on historical monthly rainfall data from 1970 to 2014.
[g]M: Cattle manure.

3.2.3. 3-PG parameterisation

3.2.3.1. Meteorological data

Climate data from 1970 – 2005 were collated from the nearest weather stations to establish historical mean monthly rainfall and to determine the duration of the dry season (Figure 3.2a). Current (2006 – 2014) monthly rainfall, mean minimum and maximum monthly temperatures, and monthly mean daily solar radiation (W m^{-2}) were recorded hourly as means based on measurements at 10 min intervals over the measurement period (2006 – 2014) using an automatic weather station located close to the calibration sites (Figure 3.2a); current mean monthly rainfall at the validation sites was obtained from the nearest weather station (Figure 3.2b). Solar radiation was converted to MJ m^{-2} day^{-1} while mean *VPD* for each hour was calculated as half the difference between the saturated vapour pressure at maximum ($T_{\max}$) and minimum ($T_{\min}$) temperatures for that hour (Landsberg, 1986).

3.2.3.2. Plantation growth measurements

Diameter at breast height over bark at 1.3 m (*DBH*), tree height (*H*) and stem number in each sample plot were measured at six-monthly intervals from 2009 to 2014. These measurements were used to estimate plot *DBH*, *SV*, *MAI*, and *BA*. Ten plots, three each in CN1 and CN2 and four in CN3, were used (Table 1). The volume (*V*) of each individual stem was calculated as:

$$V = \frac{\pi}{4} \times DBH^2 \times H \times f \qquad (3.1)$$

Where *H* (m) is total stem height of an individual tree and *f* is a stem form factor (*f* = 0.495) (Binh, 2003). This same equation was used throughout the study as *f* was not significantly different between ages and sites. Stand volume (*SV*) and *BA* were then calculated as the sum of *V* and sum of the cross sectional area over bark at breast height, respectively, of all individual trees in each plot and expressed on a per hectare basis. The *MAI* was calculated by dividing the *SV* of a plot by stand age.

3.2.3.3. Biomass partitioning

Nine trees, three from each of CN1, CN2 and CN3, were harvested in September 2012. The selected trees in each stand were one mean tree, one of +1 standard deviation (SD) and one of –1 SD, based on *DBH* and *H*. For each tree, the green crown length, defined as the distance along the stem from the point of emergence of the lowest green branch and the *H* of the tree, was divided into three canopy zones of equal length; lower, middle, and upper. Stem diameters were measured at 0.1 m, 1.3 m (*DBH*), and at the base of the three canopy zones. Diameters of all live branches were measured 4 cm from the stem and the branches removed flush from the stem. Five branches that represented the range of branch diameters were selected from each canopy zone and the fresh biomass of their branches and leaves were obtained and weighted for green bulk samples. Five wood discs (30 – 40 mm cross-sections) were cut at 0.1 m, 1.3 m, and at the base of the lower, middle, and upper zones, and the stem was then cut into 1.0 m billets. The wood and bark of the discs and billets were separated and their fresh weights determined.

A randomly-selected subsample of five branches in each zone, giving 15 subsamples for each tree, was collected for oven dry. The leaves net of the petiole were excised from each branch and the fresh mass of each determined. These thirty subsamples were then dried to constant weight at 65 °C. The dry mass of the five wood disks and their bark was similarly obtained. Stem dry biomass for each crown zone was calculated from stem volume and stem wood density (Section 2.3.5). Stem volume was determined using the method described in (Quentin et al., 2011).

For each tree, the root biomass was excavated from either an area of 9 m^2 (3 × 3 m) at CN1 and CN2 or 6 m^2 (3 × 2 m) at CN3, the boundary being defined as the point equidistant between sample and neighbouring trees. Roots were harvested by hand at four soil depths: 0 – 20, 20 – 40, 40 – 60 and >60 cm and separated into three root classes: fine (<2 mm), medium (2 – 5 mm) and coarse (>5 mm). The subsamples were oven-dried to constant weight at 65 °C and weighed separately to estimate dry root mass. Total below-ground dry biomass of each tree was calculated by summing fine, medium and coarse root dry mass corresponding to each soil depth.

From the destructive biomass harvest, allometric equations for each crown zone were developed from the representative branches based on branch diameter over bark, leaf area per branch, and branch and foliage dry biomass. The dry mass:fresh mass ratio was used to calculate the total dry mass of branches and leaves in each zone. Woody biomass was calculated as the sum of the stem, bark and branch biomass. Total stem, branch, bark and foliage biomass were calculated by summing individual organ dry weight (kg $tree^{-1}$). Total above-ground dry biomass was calculated as the sum of stem, branch, bark and foliage biomass. Whole-tree biomass was calculated as the sum of above- and below-ground biomass and these values were used to develop allometric equations between *DBH* and W_{stem}, W_{foliar}, W_{root} as:

$$W_{\text{stem}} = 0.0835DBH^{2.6171} \qquad (n = 9;\ R^2 = 0.99) \tag{3.2}$$

$$W_{\text{foliar}} = 0.0283DBH^{2.2273} \qquad (n = 9;\ R^2 = 0.98) \tag{3.3}$$

$$W_{\text{root}} = 0.0504DBH^{2.22} \qquad (n = 9;\ R^2 = 0.97) \tag{3.4}$$

W_{stem} included stem, branches and bark. W_{foliar} did not include litterfall. The branch and bark fractions were determined using an exponential decay function to a non-zero asymptote (Eq. 3.5):

$$p_t = 0.1 + (0.7 - 0.1)e^{-(ln2)\left(\frac{t}{2.0}\right)^2} \tag{3.5}$$

Where t = stand age (year) was used to parameterise the branch and bark biomass fraction (p_{B}). The branch and bark fractions were 0.7 for age zero (p_{B0}) and 0.1 for mature stands (p_{B1}); the age at which p_{B} has a median value was 2 years.

3.2.3.4. Specific leaf area

Specific leaf area for young and mature stands (σ, m^2 kg^{-1}) was determined from a sub-sample of 20 representative fresh leaves from each of the five branches for each crown zone of the nine harvested biomass tress. After area measurement, the leaves were dried to constant weight at 65 °C, cooled over desiccant, and weighed. Leaf area was measured using CAN-EYE V6.3.3 software. The σ for each branch was calculated as the ratio of leaf area to leaf dry weight; the average values of σ at ages 1, 3 and 6 years were 11.7 ± 0.1, 7.1 ± 0.2 and 4.5 ± 0.3 m^2 kg^{-1}, respectively. Forty-five five-month-old nursery seedlings, 15 each of 20, 25 and 30 cm height were sampled to estimate σ at age zero (σ_0). Average σ_0 was 12.5 ± 0.1 m^2 kg^{-1}. These observed values and a function developed by Sands and Landsberg (2002) were used to develop a relationship between σ and t; the σ for mature stands (σ_1) was 4.0 m^2 kg^{-1} and the age at which σ has a median value was 2.5 years.

$$\sigma_t = 4.0 + (12.5 - 4.0)e^{-(ln2)\left(\frac{t}{2.5}\right)^2} \tag{3.6}$$

3.2.3.5. Wood density

Wood basic density (ρ, kg m^{-3}) was measured from the five stem disks sampled from each biomass tree. To increase the reliability of the values, cores were sampled at breast height from 30 additional trees aged 3 and 6 years using an increment borer. The fresh volume of under- and over-bark disks and wood cores were measured by using the water displacement method (Olesen, 1971). All discs and wood cores were then oven dried to constant weight at 65 °C to estimate dry biomass. Wood basic density was calculated as dry biomass per unit of volume.

3.2.3.6. Stomatal conductance

Six 3-yr-old trees of mean diameter, two each from the three plots sampled at CN2, were used to measure stomatal conductance (g_s, m s^{-1}). Crown length of each tree was divided into two zones of equal length (upper and lower). Leaves from each crown zone were measured hourly from 06:00 to 17:00 h local time for up to seven days in

September 2013 (wet season) and February 2014 (dry season) respectively, using a Li-1600 Steady State Porometer (Li-Cor, Lincoln, NE, USA). The values of g_s used were averages from the two canopy zones. These were used to establish the response of g_s to increasing *VPD* (Landsberg and Waring, 1997) and for parameterising the model.

3.2.3.7. Leaf area index

Leaf area index of CN2 and CN3 was estimated with an LAI 2000 plant canopy analyser (Li-Cor, Lincoln, NE, USA) using the two-sensor method. The reference sensor was located in an open area. Ten sensor points in two diagonally parallel lines through the middle of each plot were installed at 1.5 m height above ground and 3.0 m apart. Two replicated sets of measurements were made with the second sensor in the early morning and late afternoon in the absence of direct solar radiation. Measurements were made in the dry (February 2014) and rainy (September 2012 and July 2012) seasons at the CN2 and CN3 sites. Values of *LAI* were calculated using an equation developed by Battaglia et al. (1998):

$$LAI = 1.54PAI - 0.11 \qquad (R^2 = 0.99) \tag{3.7}$$

Where *PAI* represents the plant area index as measured by the LAI 2000.

Trees in the CN1 site were too small to measure *LAI* accurately using the LAI 2000. Instead, their *LAI* was estimated from leaf area obtained for 60 representative leaves harvested from the three plots (20 leaves each). Leaf area was measured using Fuji-win 32 software and then oven dried at 65 °C to constant weight. The total leaf area was calculated from an allometric equation between the leaf dry biomass of 60 leaves and total leaf dry biomass (Schindelin et al., 2012).

3.2.3.8. Litterfall

Litterfall was collected monthly between August 2012 to December 2014 from fifty 1 × 1 m square traps. Five litter traps were located in each plot at CN1 (3 plots), CN2 (3 plots) and CN3 (4 plots), one in each corner of the plot plus one in the centre. Each litter trap was suspended 1 m above the ground. Litterfall was separated into leaves, flowers, fruits, bark and twigs (<10 mm diameter) and oven-dried to constant weight at 65 °C. Based on the observed data and using an equation (Eq. 8) developed by Sands and Landsberg (2002):

$$\gamma_{F_t} = \frac{3 \times 10^{-5}}{0.001 + 0.029e^{-0.286t}} \tag{3.8}$$

The maximum litterfall rate ($\gamma_{\mathrm{F}x}$) was 0.03 month^{-1}, the default rate at age t = 0 ($\gamma_{\mathrm{F}0}$) was 0.001 month^{-1} (Sang, 2008), and the age at which litterfall rate has median value ($t_{\gamma\mathrm{F}}$) was 12 months.

3.2.3.9. Soil moisture

Three capacitance probes (EasyAG 50 cm, Sentek Sensor Technologies, SA, Australia) were installed to 50-cm depth below the ground at CN2, one each in the centre of the three plots and half way between two trees within the same row. Soil moisture content was recorded at 30 min intervals in 10 cm steps from the soil surface to a depth of 50 cm between March 2014 and April 2015. Some data was lost because of operational problems related to high humidity and soil acidity. Available soil water for the soil profile to 1.4 m, the depth that defined the limit of root development, was calculated from the measured soil water contents. As the soil texture remained constant between 50 and 140 cm depth, the water content in this part of the profile was assumed to have the same value as that measured at 50 cm.

3.2.3.10. Soil properties and soil fertility rating

Soil fertility rating, *FR* was based on an estimation of the correlation of soil properties determined just before planting for the three calibration and 12 validation sites. This is used to calculate the value of the growth modifier f_{FR} (Sands and Landsberg, 2002). Three plots were established at each site and a 10-cm diameter auger used to randomly collect nine soil samples from each of two depths, 0 – 10 and 10 – 20 cm. The samples at each depth from each plot were aggregated into a composite. Preparation and analysis of the composite soil samples were carried out according to van Reewijk (2002).

Soil samples were air-dried and sieved to <2 mm, followed by oven drying at 65 °C to constant weight. Soil pH_{H_2O} was measured in a 1:2.5 mixture of soil and distilled water, and pH_{KCl} in a 1:5 mixture of soil and 1M potassium chloride. Exchangeable K^+ was determined by flame photometry and Ca^{2+} and Mg^{2+} by atomic absorption spectroscopy following extraction in 1M NH_4Cl. Available P (avail. P) was determined following extraction by Bray-I solution containing 1M NH_4F and 0.5M HCl. Soil organic carbon (SOC) and total nitrogen (TN) were analysed using the Walkley-Black and Kjeldahl methods, respectively. Soil bulk density (BD) was determined from cores that had been dried at 105 °C to constant weight. Gravel (>2 mm) in each BD core was separated and weighed. Soil sub-samples (50 g air-dried <2 mm) were used to determine particle size following the method of Robinson (see van Reeuwijk 2002).

To establish *FR*, a three-stage process was used. First, *FR* values were allowed to vary and optimum values were calculated for each site to establish the best fit between observed and predicted *DBH*. Second, relationships between the best-fit *FR* values obtained for each plot (independent variables) and the explanatory soil variables (dependent variables) were examined by linear regression. Correlations between *FR* and the dependent variables were then explored using stepwise regression in SAS/STAT (Ver. 9.3, SAS Institute Inc., Cary, NC, USA) to examine which of the soil variables could best explain the *FR*. Finally, the equation developed was applied at each site to estimate *FR*.

3.2.4. Model sensitivity analysis

In order to identify the most important parameters to be measured, sensitivity analysis (SA) was carried out to examine the influence of the parameter values on the main outputs (Battaglia and Sands, 1998a; Esprey et al., 2004).

The SA was based on two stand ages (7 and 15 years) for twenty-one parameters. In each model run, the SA was performed for a selected model output at each time step, was based on changes of ± 10% and ± 20% to the parameter values in the calibration, and examined the effects on the model *DBH*, W_{stem}, W_{foliar}, W_{root}, *LAI*, and *WUE* outputs.

3.2.5. Model validation

Model validation was conducted by comparing modelled outputs with observed measurements of *DBH*, *SV*, *MAI* and *BA* at the twelve validation sites. Stocking, *H* and *DBH* had been measured in 55 plots at six-monthly intervals at the validation sites. Estimates of *SV*, *MAI*, and *BA* were carried out as for the calibration process. Five trees representing the range of diameter classes were felled at four sites (VNC4, VNC5, VSC6 and VSC7) during their rotation to estimate total stand above-ground biomass (TW_{AGB}, Mg ha^{-1}) (unpublished data, see Dung et al., 2012 for methods of biomass sampling). For VNC4, trees were felled at ages 1.1, 2.9, 4.0 and 4.9 years, VNC5 at 1.1, 2.1 and 3.2 years, VSC6 at 1.0, 2.0 and 3.0 year and VSC7 at 1.2, 1.9, 2.9, and 3.9 years.

Hourly meteorological data (rainfall, air temperature and solar radiation) were obtained from seven automatic weather stations located nearest to the twelve experimental sites (two in VN, one in VNC, one in VSC and three in VS) (Table 3.1). Figure 3.2b shows mean monthly rainfall during the measurement period of the study at the twelve validation sites. The soil sampling and associated analysis were as described for the calibration sites (Table 3.2). Simple linear regressions were performed to determine the relationship between modelled and measured values.

The fit between the predicted and observed values was assessed through regression statistics and calculating model efficiency (*EF*); the *EF* values can vary from –1 (no fit) to +1 (perfect fit) (Loague and Green, 1991) where:

$$EF = \frac{\sum_{i=1}^{n}(O_i-\bar{O})^2 - \sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \quad (3.9)$$

Where P_i and O_i are the predicted (P_i) and observed values respectively, $\bar{P}$ and $\bar{O}$ are the mean of the predicted and observed values respectively and n is the total number of datasets. The best model efficiency should have *EF* and the coefficient of determination (R^2) close to unity. In addition, the root mean squared error (*RMSE*) was used to make comparisons of the precision of the estimates in the same units as the dependent variable (Janssen and Heuberger, 1995) where:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \tag{3.10}$$

Relationships of predicted and observed for *DBH*, *SV*, *MAI*, *BA*, *LAI* and available soil water (*ASW*) of the study regions were examined by linear regression. Group regression analysis (McPherson, 1990) was used to examine regional differences in the slopes and intercepts of the regression relationships between predicted and observed *DBH*, *BA*, *SV* and *MAI*. An analysis of the relative growth constraints (modifiers) f_{ASW}, f_{VPD}, f_{T}, and f_{FR} was used to explain how these constraints affect productivity. The model was also used to generate the lengths of dry seasons across regions based on an average of modifier values in consecutive months receiving $\leqslant$40 mm mean monthly rainfall. All modifiers were varied from zero (representing total limitation) to one (no limitation). Multiple comparisons were carried out at a significance level of 0.05 to protect against type I error. All analyses were performed on SAS/STAT (Ver. 9.3, SAS Institute Inc., Cary, NC, USA).

3.3. Results

3.3.1. Soil variability and fertility rating

The study sites had large differences in soil physical and chemical properties (Table 3.2). For physical properties, these were found in the textural classes, sand (7 – fold range), silt (4 – fold) and clay (>2 – fold); and for chemical properties soil pH (pH_{H_2O} = 3.4 – 5.7 and pH_{KCl} = 3.1 – 4.6), TN (5.5 – fold), SOC (3.5 – fold), avail. P (7.4 – fold), Mg^{2+} (4.2 – fold), Ca^{++} (20 – fold) and K^+ (2.9 – fold). The Ferralic Acrisols at VS9 and VS11 had amongst the highest TN (0.19; 0.22%), SOC (3.3; 3.9%) and Sum(K^+, Ca^{2+}, Mg^{2+}) (0.48; 0.57 cmol kg^{-1}) although levels of avail. P (2.3; 3.2 mg kg^{-1}) were low. The Rhodic Ferralsols at VNC3, VNC4 and VNC5, and the Haplic Acrisols at VSC6 and VSC7 had amongst the lowest TN (0.04 – 0.13%) and SOC (1.1 – 1.8%); avail. P at VNC3 and VNC4 was 2.9 and 5.8 mg kg^{-1}, respectively; Sum(K^+, Ca^{2+}, Mg^{2+}) was high (0.42 – 0.55 cmol kg^{-1}) except VSC6 had amongst the lowest values (0.17 cmol kg^{-1}). The Ferralic Acrisols at VN1 and VN2 had lower TN (0.11; 0.18%), SOC (1.7; 2.1%) and Sum(K^+, Ca^{2+}, Mg^{2+}) (0.21; 0.23 cmol kg^{-1}) than the same soils at VS9 and VS11 but higher avail. P (4.4; 4.9 mg kg^{-1} at VN1 and VN2 *vs*. 2.3; 3.2 mg kg^{-1} at VS9 and VS11); the Ferralic Acrisol at VS10 had amongst the lowest TN and SOC and highest avail. P (13.3 mg kg^{-1}) and Sum(K^+, Ca^{2+}, Mg^{2+}) (0.50 cmol kg^{-1}). The Gleyic and Chromic Acrisols, respectively, at VS8 and VS12 also had low TN (0.07; 0.14%) and SOC (1.1; 2.0%) and high levels of avail. P (5.8; 11.1 mg kg^{-1}); Sum(K^+, Ca^{2+}, Mg^{2+}) was 0.42 cmol kg^{-1} at VS8 and 0.17 cmol kg^{-1} at VS12.

Linear regression showed that *FR* was positively correlated with K^+ ($FR = 4.3037K^+ - 0.0038$, $R^2 = 0.75$, $p < 0.0001$), Ca^{2+} ($FR = 2.8415Ca^{2+} + 0.3275$, $R^2 = 0.51$,

p = 0.004) and Mg^{2+} ($FR = 2.0639Mg^{2+} + 0.3231$, $R^2 = 0.43$, $p = 0.011$) as well Sum(K^+, Ca^{2+}, Mg^{2+}) (FR = 1.2983Sum(K^+, Ca^{2+}, Mg^{2+}) + 0.1283), $R^2 = 0.71$, $p < 0.0001$); the slopes were higher for K^+ and Ca^{2+} than Mg^{++} and Sum(K^+, Ca^{2+}, Mg^{2+}), indicating the greater effects of K^+ and Ca^{2+} on *FR*. Stepwise regression analysis showed that *FR* was best explained by K^+, Ca^{2+}, and SOC ($FR = 2.3868K^+ + 2.3351Ca^{2+} + 0.0814SOC - 0.0992$, $R^2 = 0.91$, $p < 0.0001$) and it was this result that was used to calculate *FR* in this study. However, for the five sites in VS, an adjustment of ± 0.1 units (Fontes et al., 2006) was required to best fit model prediction. Fertility Rating varied from 0.3 to 0.8 (Table 3.2).

Table 3.2 Soil properties and fertility rating (*FR*) of the calibration and validation sites.

Site	Soil type (FAO, 2006)	Clay	Silt	Sand	Gravel	pH		SOC	Avail. P	TN	Ex-Ca	Ex-K	Ex-Mg	Sum (Ca^{2+}, K^+, Mg^{2+})	Fertility rating
		(%)				H_2O	KCl	(%)	(mg kg^{-1})	(%)	(cmol kg^{-1})				(*FR*)
CN1	Ferralic Acrisols	28.9	62.3	8.8	-	3.7	3.2	2.7	3.4	0.16	0.06	0.12	0.08	0.26	0.4
CN2	Ferralic Acrisols	28.9	62.1	8.9	-	3.4	4.6	2.6	1.8	0.16	0.01	0.12	0.06	0.19	0.4
CN3	Ferralic Acrisols	24.4	51.3	21.2	3.1	3.7	3.2	1.6	3.9	0.15	0.07	0.08	0.08	0.24	0.4
VN1	Ferralic Acrisols	21.3	42.0	21.9	15.0	3.6	3.1	2.1	4.4	0.18	0.07	0.09	0.07	0.23	0.5
VN2	Ferralic Acrisols	22.5	45.5	26.6	5.3	4.4	3.6	1.7	4.9	0.11	0.05	0.11	0.05	0.21	0.4
VNC3	Rhodic Ferralsols	27.6	18.4	32.9	11.1	4.2	3.7	1.6	2.9	0.13	0.10	0.13	0.21	0.44	0.6
VNC4	Rhodic Ferralsols	18.2	35.1	38.3	8.4	4.9	4.0	1.8	5.8	0.11	0.14	0.16	0.25	0.55	0.6
VNC5	Rhodic Ferralsols	19.8	29.0	51.0	-	4.7	4.0	1.4	-	0.12	0.09	0.12	0.21	0.42	0.6
VSC6	Haplic Acrisols	22.3	14.8	62.7	-	5.7	4.4	1.2	-	0.04	0.04	0.07	0.06	0.17	0.3
VSC7	Haplic Acrisols	23.4	15.9	60.5	-	5.7	4.4	1.1	-	0.04	0.20	0.11	0.17	0.48	0.4
VS8	Gleyic Acrisols	27.8	18.1	20.1	34.0	4.6	4.0	1.1	5.8	0.07	0.07	0.20	0.15	0.42	0.7
VS9	Ferralic Acrisols	20.7	58.1	21.2	-	4.3	3.5	3.9	2.3	0.22	0.17	0.20	0.20	0.57	0.8
VS10	Ferralic Acrisols	15.8	24.1	60.0	-	5.2	4.2	1.1	13.3	0.08	0.13	0.16	0.21	0.50	0.8
VS11	Ferralic Acrisols	29.6	57.3	13.1	-	4.0	3.5	3.3	3.2	0.19	0.17	0.18	0.13	0.48	0.8
VS12	Chromic Acrisols	13.6	20.3	56.6	9.5	4.7	3.9	2.0	11.1	0.14	0.04	0.07	0.06	0.17	0.8

3.3.2. Modelling plantation growth

Using parameter values for the calibration sites (Appendix Table 3.1), there was good agreement between observed and predicted values of eight outputs (*DBH*, *BA*, *SV*, *MAI*, W_{stem}, W_{foliar}, W_{root} and *LAI*), (*EF* ranged from 0.76 to 0.98) for a rotation length of 15 year (Figure 3.3). The model was least accurate in predicting *DBH* and *MAI* of CN3 at ages $\leqslant$4 year (*EF* = 0.86 and 0.60, respectively), but was able to predict both variables at later stages of growth with better accuracy (Figure 3a, d) (*EF* = 0.89 and 0.94, respectively). Differences between measurements and predictions of *DBH*, *SV*, *MAI*, and W_{stem} (Figure 3.3a, c, d, e) were greater in CN1 and CN2 than CN3 except for W_{root} (Figure 3.3g), although these differences were generally smaller for all variables at ages >3 year (*EF* <0.86). Differences between predicted and observed values of *BA* and W_{foliar} were less pronounced (Figure 3.3b, f), and the model closely tracked *LAI* (Figure 3.3h) (*EF* > 0.91).

There was good agreement between predicted and observed values for *DBH*, *BA* and *SV* across the four regions (Figure 3.4).There was also reasonable agreement between the predicted and observed values of *MAI* in VN and VCN plantations, but *MAI* was underestimated in VS and overestimated in VSC plantations during the early part of the rotation (Figure 3.4d). At the end of 8-yr rotation, the predicted values of *DBH* and *SV* in VS were between 9.4 – 22.0% and 3.4 – 19.9% greater, respectively, than in VSC, VN and VNC (Figure 3.4a, c). Growth at sites in VS was highest (observed *DBH* at age 3 years 11.0 – 12.2 cm), intermediate at VNC (9.4 – 10.2 cm), and lowest at VSC (7.7 – 8.1 cm) and VN (8.2 – 9.2 cm) (Figure 3.4a).

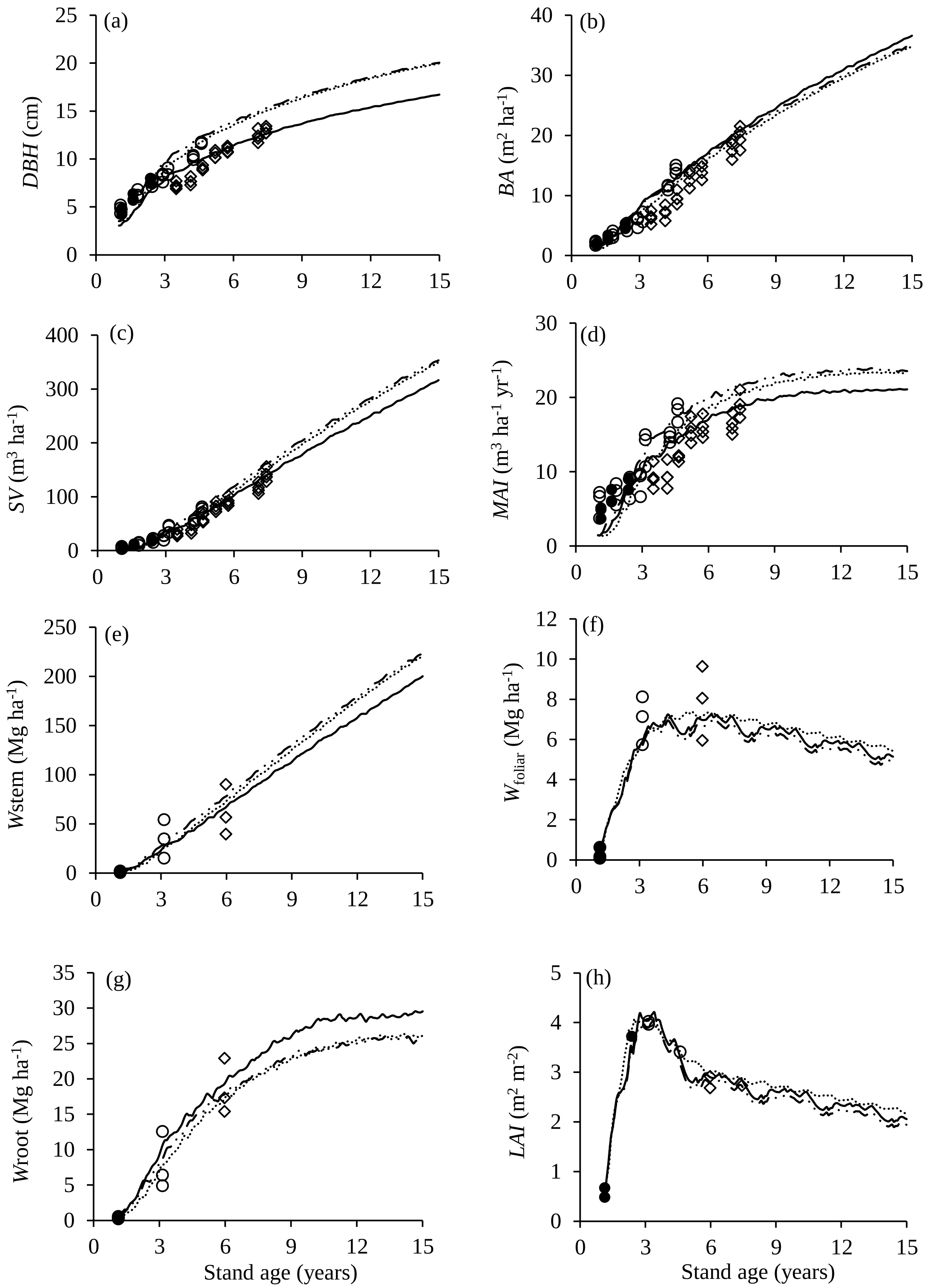

Figure 3.3 Comparisons between observed (symbols) and predicted (lines) growth of *A. hybrid* plantations at CN1 (●, ···), CN2 (○, - -), CN3 (◊, —) for a 15-yr rotation for *DBH* (a), *BA* (b), *SV* (c), *MAI* (d), W_{stem} (e), W_{foliar} (f), W_{root} (g) and *LAI* (h).

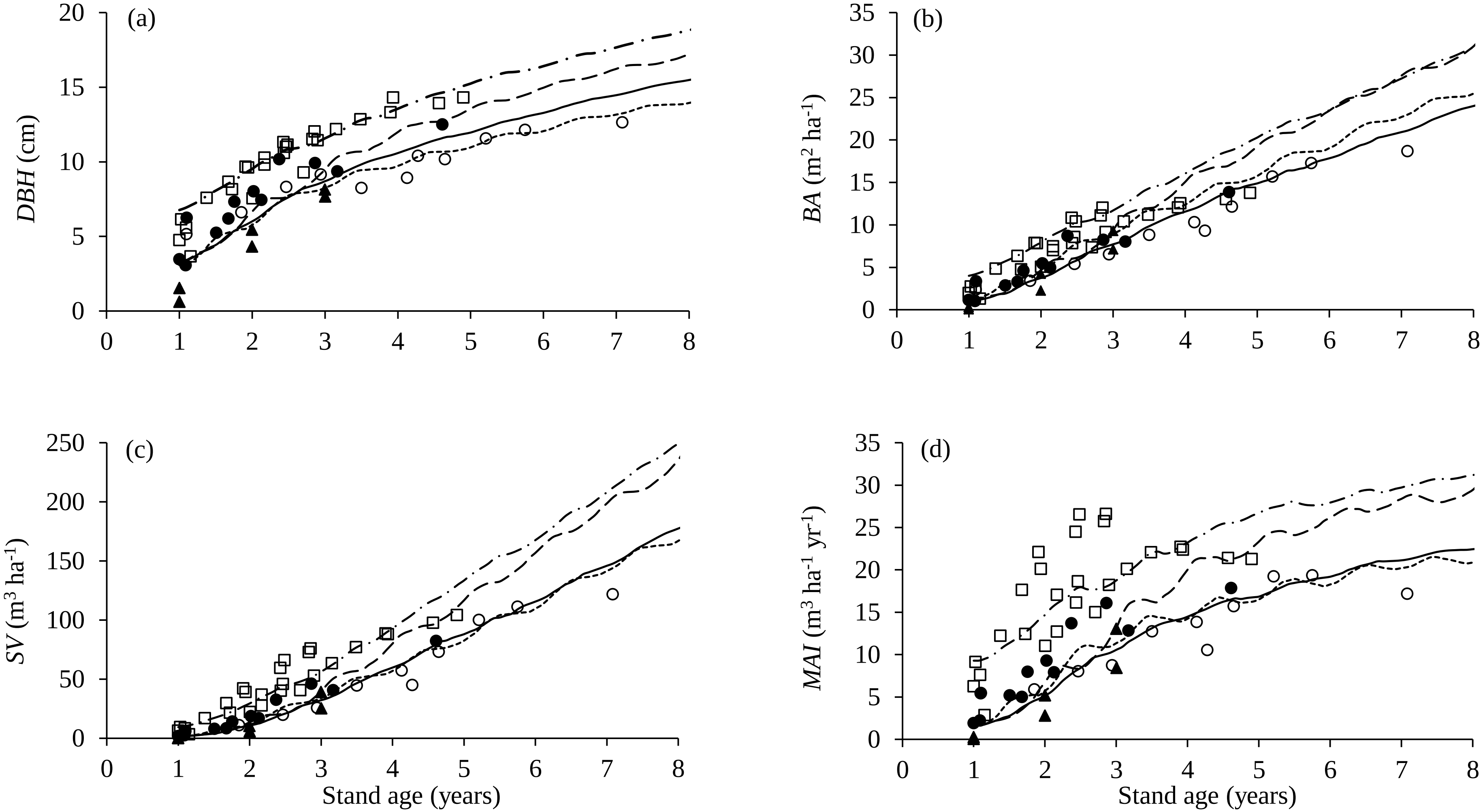

Figure 3.4 Comparisons between observed (symbols) and predicted (lines) *DBH* (a), *BA* (b), *SV* (c) and *MAI* (d) for an 8-yr rotation at the twelve validation sites in the North (○, —), North Central Coast (●, - - -), South Central Coast (▲, ···) and South (□,-·-·-).

For the calibration sites, the model accurately predicted the growth patterns of *DBH*, *BA* and *SV*; *EF* was ⩾0.88 (Figure 3.5a, b, c). The prediction of *MAI* was less accurate; *EF* was 0.76 (Figure 3.5d). For the twelve validation sites, *EF* was ⩾0.89 for *DBH*, *BA* and *SV* and 0.79 for *MAI*, and for the four validation sites where biomass sampling was undertaken, the model was more accurate in predicting W_{stem} and TW_{AGB} with *EFs* of 0.87 and 0.90, respectively (Figure 3.5e, g) than W_{foliar} with *EF* of 0.76 (Figure 3.5f). When the validation sites were divided by region, the model accounted for ⩾81% of the variance in the observed values of *DBH*, *BA*, *SV*, and *MAI*, except *MAI* for the southern sites ($R^2 = 0.70$) (Table 3.3); *DBH* and *MAI* were significantly different between sites within each region ($p < 0.001$ and 0.01, respectively), whereas differences between *BA* and *SV* were not significant ($p > 0.05$) (Table 3.3). The model was also able to produce accurate predictions of all growth variables with negligible bias for each region (*EF* = 0.74 – 0.97 and *RMSE* = 0.69 – 11.61) (Table 3.3).

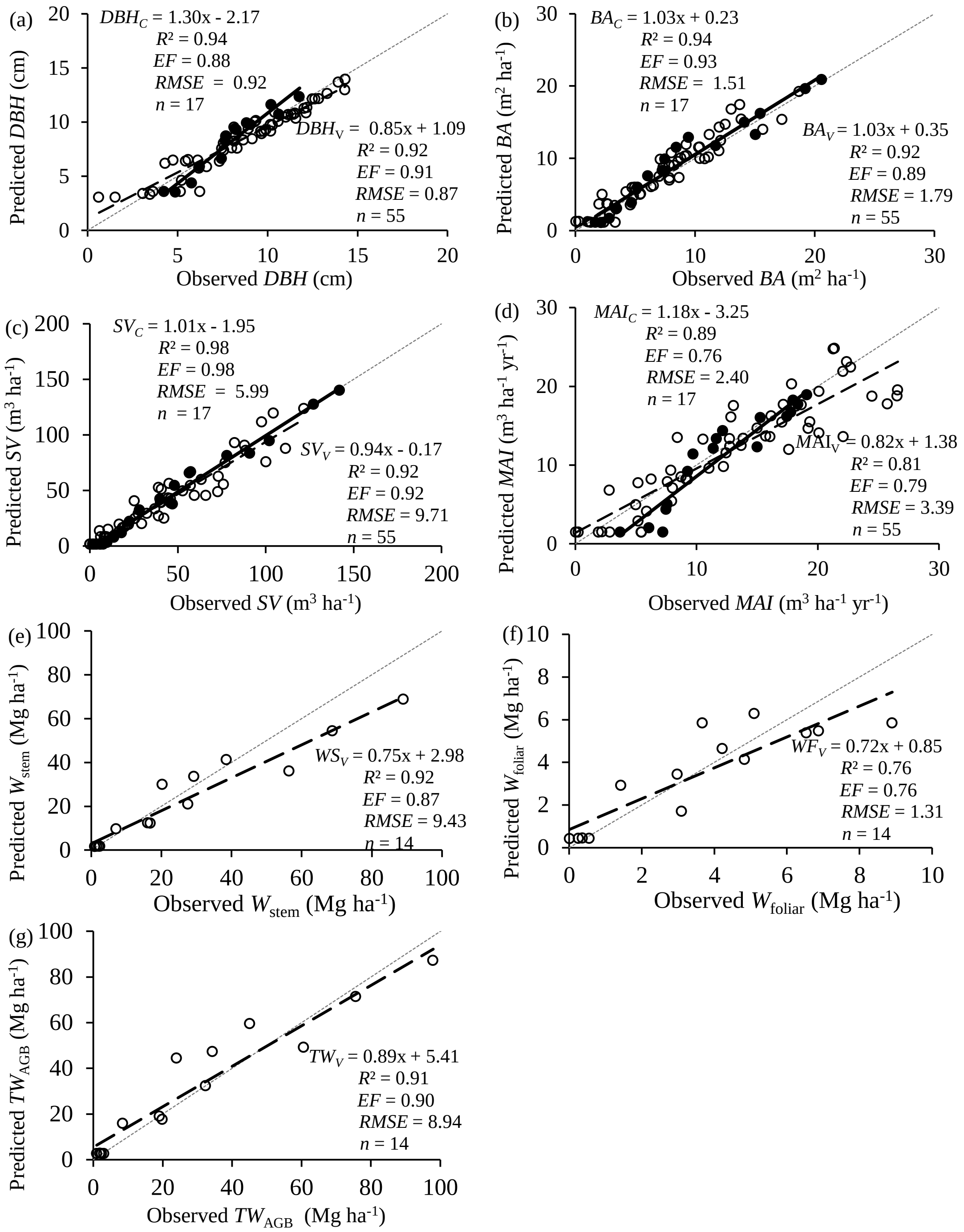

Figure 3.5 Comparisons between observed (symbols) and predicted (lines) values of the three calibration (C) (●, —) and twelve validation (V) sites (○, - - -) for *DBH* (a), *BA* (b), *SV* ((c) and *MAI* (d) at ages ranged 3 – 8 years. Dots represent means of 35 – 42 trees plot^{-1}; and for W_{stem} (e), W_{foliar} (f) and TW_{AGB} (g) of four validation sites in Central Vietnam, dots represent means of 70 biomass trees.

Table 3.3 Linear regressions between predicted and observed values of *DBH*, *BA SV* and *MAI* of *A.* hybrid at the twelve validation sites in North (VN), North Central Coast (VNC), South Central Coast (VSC) and South (VS). The number of plots measured (*n*), model efficiency (*EF*), root mean square error (*RMSE*), regression coefficient (R^2), and *p* values (n.s. = not significant; ** $p \leq 0.01$; *** $p \leq 0.001$) indicate whether means of sites are significantly different within each region. The figure in brackets is ± 1SE.

Regions	Variable	Intercept	Slope	*n*	*EF*	*RMSE*	R^2	*p* value
North	*DBH*	-1.64 (0.09)	1.19 (0.10)	11	0.87	0.83	0.93	***
	BA	-0.66 (1.08)	1.22 (0.11)	11	0.86	2.21	0.97	n.s.
	SV	-0.32 (5.64)	1.06 (0.09)	11	0.92	11.61	0.93	n.s.
	MAI	-0.56 (2.61)	1.07 (0.18)	11	0.74	2.50	0.82	**
North Central Coast	*DBH*	-0.83 (0.73)	1.01 (0.08)	12	0.91	0.93	0.81	***
	BA	-1.12 (0.96)	1.27 (0.13)	12	0.86	1.61	0.85	n.s.
	SV	-3.46 (4.85)	1.17 (0.13)	12	0.96	5.70	0.96	n.s.
	MAI	-1.99 (2.11)	1.18 (0.17)	12	0.91	2.06	0.91	**
South Central Coast	*DBH*	2.21 (1.24)	0.80 (0.10)	6	0.92	1.41	0.97	***
	BA	1.16 (1.05)	1.04 (0.18)	6	0.91	1.46	0.97	n.s.
	SV	2.60 (5.87)	1.11 (0.26)	6	0.97	4.86	0.98	n.s.
	MAI	1.87 (2.15)	1.01 (0.24)	6	0.95	2.07	0.97	**
South	*DBH*	1.35 (0.47)	0.84 (0.05)	26	0.95	0.69	0.96	***
	BA	-0.10 (0.65)	1.13 (0.07)	26	0.76	1.76	0.89	n.s.
	SV	-4.52 (3.26)	0.95 (0.06)	26	0.86	11.11	0.90	n.s.
	MAI	2.95 (1.48)	0.68 (0.08)	26	0.68	4.34	0.70	**

The model was more accurate in predicting productivity in the north (VN) and north central coast (VNC) than the south (VS) and south central coast (VSC). The slope of the relationships between predicted and observed *DBH* and *MAI* for VN and VNC (VN+VNC) were significantly different to those for VSC and VS (VSC+VS)

(Figure 3.6a, d); *EFs* were 0.91 and 0.91 (*RMSE* = 0.86 and 2.50, respectively) for VN+VNC and 0.91 and 0.76 (*RMSE* = 0.87 and 4.01, respectively) for VSC+VS, respectively. The slope of the relationship between predicted and observed *SV* for VN, VNC and VSC (VN+VNC+VSC) was significantly different to that for VS; *EFs* were 0.96 (*RMSE* = 8.27) for VN+VNC+VSC and 0.91 (*RMSE* = 11.11) for VS (Figure 3.6c). The slope of the relationship between predicted and observed *BA* was not significantly different across regions; *EF* was 0.86 (*RMSE* = 1.79) (Figure 6b). Comparison of model outputs showed that *DBH* and *MAI* were overestimated in the VSC and VS regions at <10 cm and <10 m^3 ha^{-1} yr^{-1}, respectively, and underestimated at greater values (Figure 3.6a, d).

There was good agreement between the predicted and observed monthly *ASW* (R^2 = 0.85, *EF* = 0.99) (Figure 3.7a). Observed *ASW* ranged from 70 to 230 mm and predicted from 99 to 200 mm (Figure 3.7b). This comparison between observed and predicted *ASW* showed that the model performed well at a monthly time step, however any shorter-term variability of measured soil moisture was not detected since the model time step is monthly.

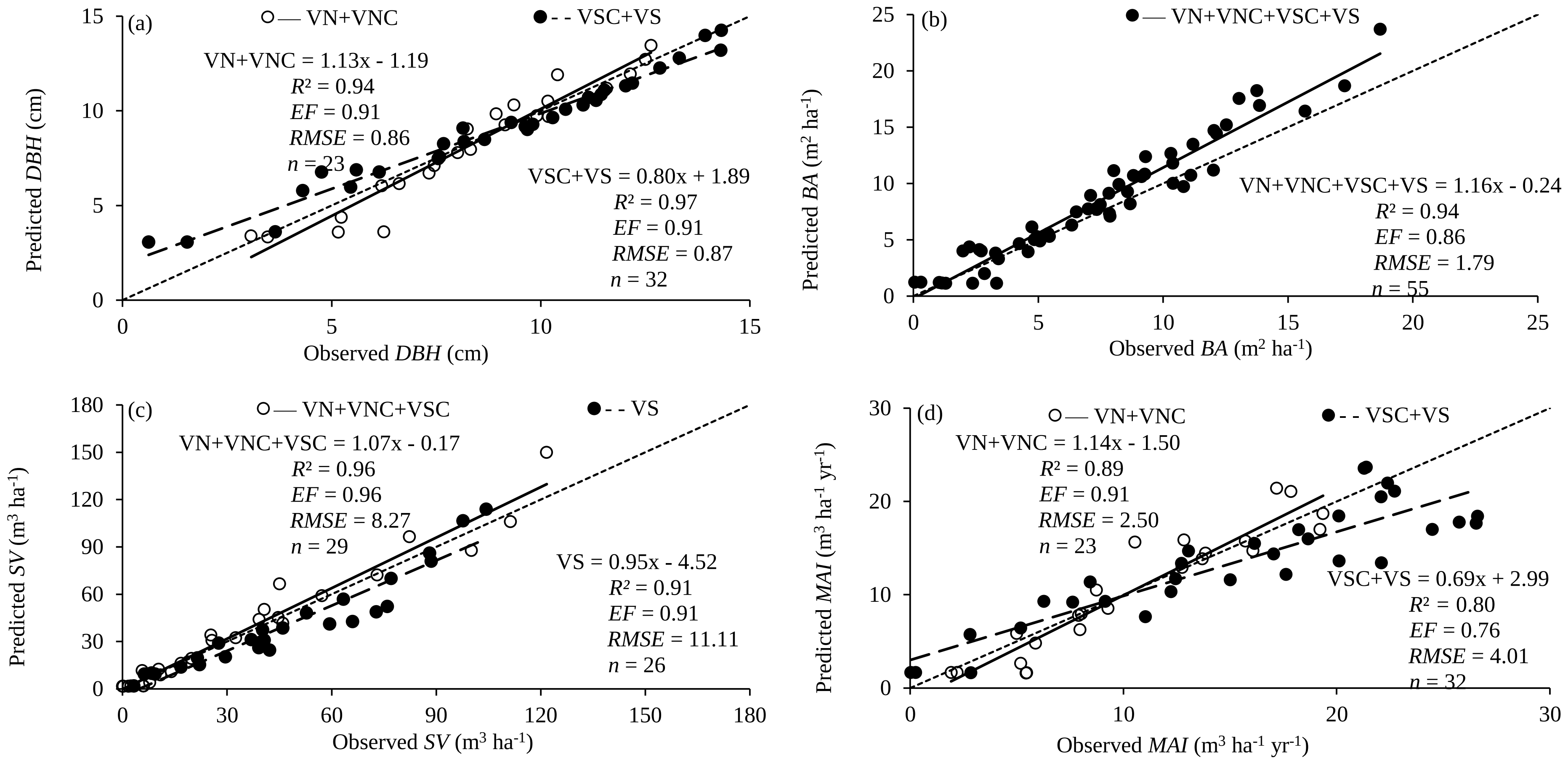

Figure 3.6 Relationships between predicted and observed *DBH* (a), *BA* (b), *SV* (c) and *MAI* (d) at ages ranged 3 – 8 years across four study regions.

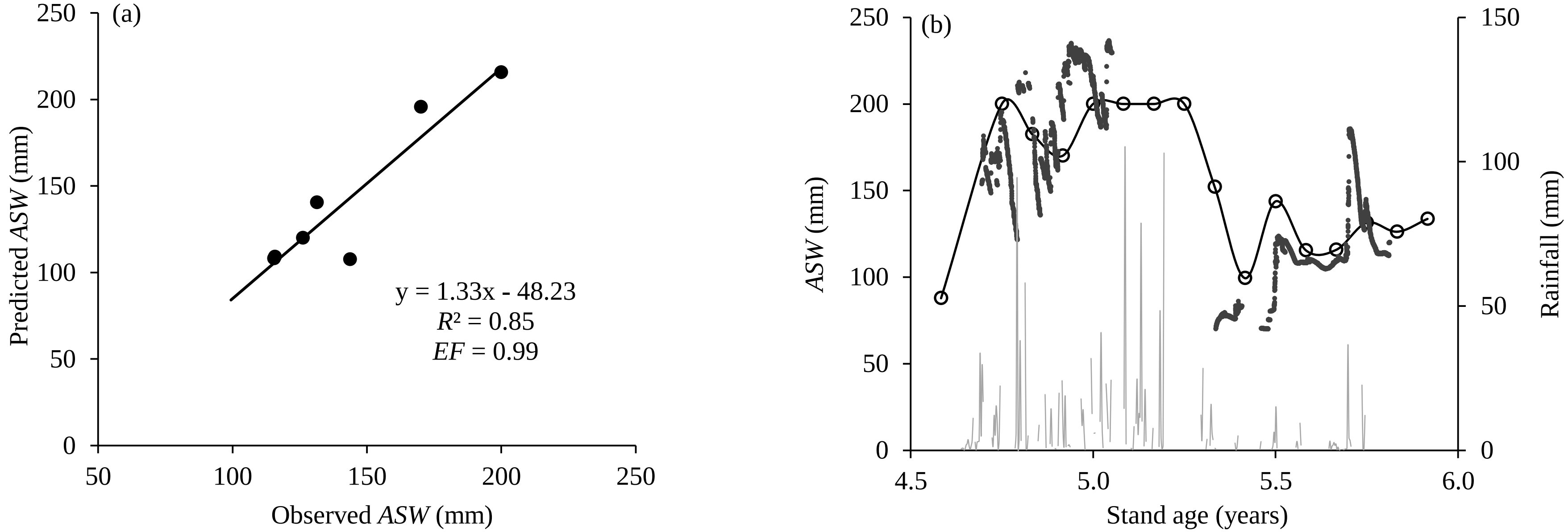

Figure 3.7 Relationshisp between observed and predicted monthly *ASW* (a) and monthly predicted (open circle) and hourly observed (solid dots) *ASW* during the period of 3/2014 to 4/2015 at CN2 (b). Daily rainfall (bars) is shown in the right-hand axis.

3.3.3. Growth limiting factors (modifiers)

The estimated mean f_{ASW}, f_T and f_{VPD} for the dry season for all sites and a rotation of 15 year were 0.58, 0.57 and 0.61, respectively (Figure 3.8a), and for the wet season 0.97, 0.70 and 0.62, respectively (Figure 3.8b). Soil fertility, with an estimated mean f_{FR} of 0.22 – 0.80, was the least important constraint to growth for both dry and wet seasons. In the dry season, *ASW*, *T* and *VPD* in VN, VCN and VSC had more impact on current monthly increment (*CMI*) (m^3 ha^{-1} $month^{-1}$) than in VS; *CMI* in these four regions was 1.53, 1.88, 1.83 and 2.64 m^3 ha^{-1} $month^{-1}$, respectively (Figure 3.8a). In contrast, *T* and *VPD* had the greatest impact on *CMI* in the wet season though the magnitude was not as large as in the dry season while *ASW* virtually had no impact on *CMI*; *CMI* of VN, VCN, VSC and VS was 2.84, 3.20, 2.93 and 3.85 m^3 ha^{-1} $month^{-1}$, respectively (Figure 3.8b).

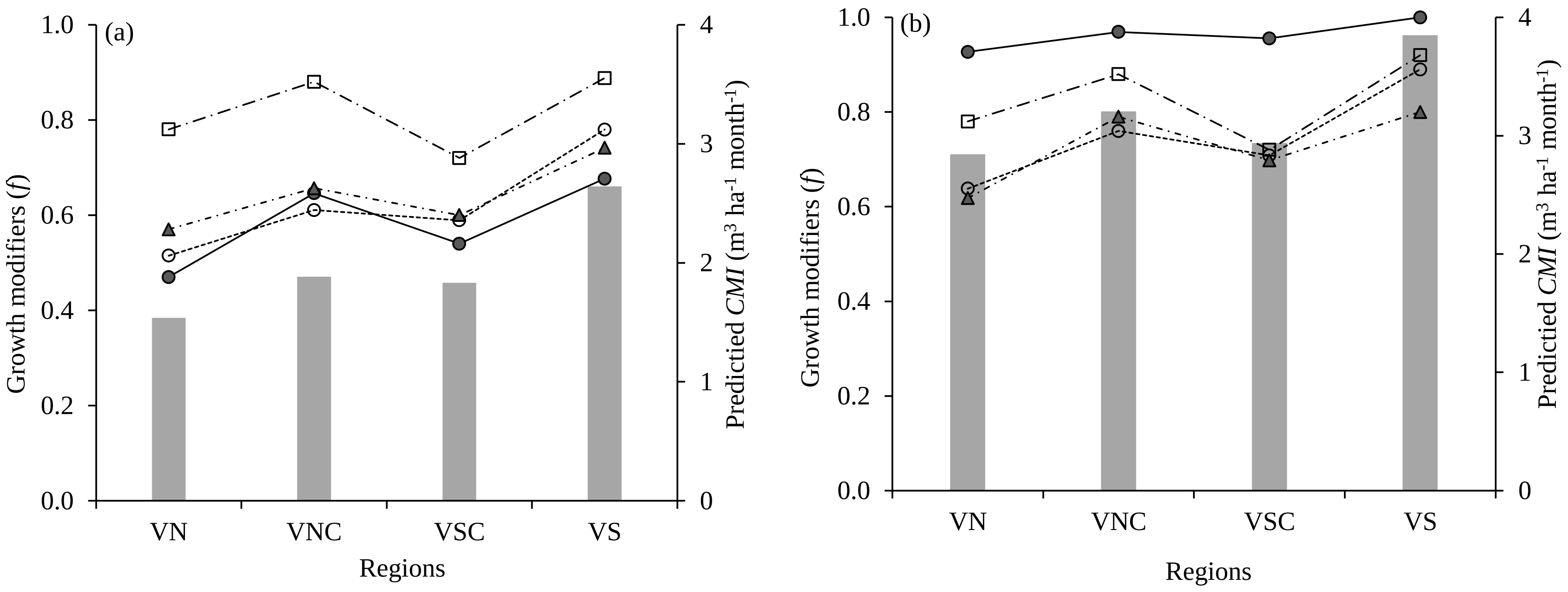

Figure 3.8 3-PG model growth modifiers at the twelve validation sites in the four study regions; f_{ASW} (—●—), f_T (- -○- -), f_{VPD} (—▲—), f_{FR} (- -□- -) and current monthly increment (*CMI*) (bars) during dry (a) and wet (b) seasons for a 15-yr rotation.

3.3.4. Sensitivity analysis

For stands at age 7 years, sensitivity analyses of 21 model parameters on six model outputs showed that when the value of the power (n_S) in the allometric relationship between stem mass and mean diameter was reduced by 20%, *DBH*, W_{foliar} and *LAI* were highly affected, respectively by -85%, -39% and -39% (Appendix Table 3.2). Similarly, a 20% reduction in optimum temperature (T_{opt}) affected these outputs and W_{stem}, W_{root} and *WUE* from between -14 and -38%. Changes of -20% in the ratio of net to gross primary production (*Y*) reduced *DBH* by -9%, W_{root} by -25% and *LAI* by 19%; the same reduction in maximum canopy quantum efficiency (α_{Cx}) has a similar range of impact on all six outputs. The parameters t_σ, a_S, k_g, p_2, η_{Rx}, and σ_0 were classified as of low sensitivity, the selected outputs only changing from between -6 and 9%.

The sensitivity of n_S, σ_1, γ_{Fx} and p_2 increased with age. Changes of +20% in n_S and γ_{Fx} increased both W_{foliar} and *LAI* by an additional 10% and 9%, respectively, at age 15 year compared to age 7 year. Others decreased with age, for example, a +20% change in n_s and γ_{Fx} decreased *WUE* (-1.6% and -10%), W_{foliar} (-16% and -25%) and *LAI* (-15% and -24%) at age 7 and 15 years, respectively.

3.4. Discussion

3.4.1. Model accuracy

Ten permanent sample plots from stands aged 1, 3 and 6 years were sufficient to satisfactorily parameterise and calibrate the model; comparisons of observed and predicted values of eight 3-PG outputs also showed that the model can reliably represent the anticipated patterns of these growth-related variables with stand age (Almeida and

Sands, 2016). However, the model better fitted the observed *DBH* and *MAI* at CN1 and CN2 than CN3. The lower predicted productivity at CN3 may be linked to the different clonal mixture planted at this site as it contained a greater proportion of clones that have lower than average *DBH* and more variable wood density than of those planted at CN1 and CN2 (Kha et al., 2012). Clonal variation between allometric parameters can result in differences in predictions of *SV*, W_{stem} and *LAI* (Almeida et al., 2004b); the random clonal mixture planted at all three calibration sites meant that it was not possible to identify which clones were measured or harvested during biomass sampling. Also, unlike CN1 and CN2, the harvesting slash was removed prior to planting at CN3 which can lead to lower productivity (Huong et al., 2014); CN3 also had lower SOC and had received less fertiliser at planting. Nevertheless, all three calibration sites had the same initial *FR* values (*FR* = 0.4). Soil physical characteristics, which were also different at CN3, can affect rates of growth of tropical acacias (Sam, 2001; Son, 2006). Uncertainties associated with soil characteristics can affect model prediction (Almeida et al., 2010a; González-García et al., 2016) but understanding and quantifying variability and how this translates to model behaviour is a challenging task.

A single set of parameters enabled 3-PG to estimate the growth and productivity of *A.* hybrid plantations across a wide range of climates and soils at the twelve validation sites with high accuracy; *EF* for *MAI* (= 0.79) and W_{foliar} (= 0.76) were lower but acceptable. Together, the model efficiencies were either similar to or higher than reported for other species over a wide range of locations (Paul et al., 2007; Almeida et al., 2010a; Pérez-Cruzado et al., 2011; Almeida and Sands, 2016; González-García et al., 2016). For *A. mangium* in Vietnam, the *EF* for *MAI* was 0.77 (Sang, 2008), almost identical to that found in this study. The relatively lower *EF* for *MAI* than for the other growth variables is a common finding, for example for *E. grandis* × *E. urophylla* hybrids in Brazil *EF* for *DBH*, *SV* and *MAI* was 0.87, 0.83 and 0.65, respectively, and is linked to a combination of factors such as wood density variation, ramet quality, reduction in *LAI* as the plantation ages and climatic variation (Almeida et al., 2010a). The relatively low *EF* for W_{foliar} is considered due to uncertainty in the estimation of the litterfall parameter, γ_{Fx} which is derived as a constant fraction of W_{foliar}. However, its value will inevitably vary as W_{foliar} changes with season and growing conditions (Almeida et al., 2004b; Fontes et al., 2006).

3.4.2. Productivity variation across four regions

Accuracy of prediction of *DBH* and *MAI* was greater at VN and VNC than VSC and VS. Growth of *DBH* and *MAI* was greatest at VS, intermediate in VNC and VSC, and least at VN. Thus the highest predicted productivity was associated with warmer mean annual temperatures and the most fertile soils as represented by their *FR*. This finding was also consistent with species and provenance trials in Vietnam that note faster early growth of *A.* hybrid with decreasing latitude from 21°N to 10°N (Nghia and Kha, 1998; Kha et al., 2012) and for *A. mangium* across similar latitudes in other tropical countries (Harwood and Williams, 1992).

The model detected regional differences in growth patterns, for *DBH* and *MAI* between VN+VNC and VSC+VS), for *SV* between VS and VN+VNC+VSC; for *BA* all regions were in a single group. This may be attributed to differences in the *DBH*, wood density and stocking rates which were used to calculate *BA*, *SV* and *MAI* where small variations in their values can have different effects in each region (Almeida et al., 2010a). As has been found previously, 3-PG accurately predicted *MAI* at VN and VNC where the sites had average productivity but over- and under- predicted *MAI* at the low (VSC) and high (VS) productivity sites, respectively (Almeida et al., 2010a; González-García et al., 2016).

3.4.3. Factors limiting productivity at the regional level

Water limitation is potentially a major factor limiting acacia productivity across Vietnam as the dry seasons where the plantations used for this study had been established were up to five consecutive months in length; and in the context of the 3-PG growth modifiers, f_{ASW} was generally the most limiting for growth during this season in all regions ($f_{\mathrm{ASW}} \leq 0.58$). Nevertheless, the levels of water stress appear to be much less than can happen in Mediterranean environments during the dry season where $f_{\mathrm{ASW}} < 0.2$ can be experienced and, unlike in this study, monthly growth increments can drop to zero (González-García et al., 2016). At the calibration sites at Ba Vi, observed values of *ASW* were never less than about one-third of field capacity, and in Central Vietnam, pre-dawn water potential of *A*. hybrid was still > -0.5 MPa, even at the end of the dry season, suggesting that no more than mild water stress had developed (T. L. Dong; unpublished data). However, for *Acacia auriculiformis* in southern Vietnam, the dry season was still associated with reduced growth increments (Huong et al., 2008) as predicted in this study, where the mean *CMI* across the four regions was 3.21 and 1.97 m^3 ha^{-1} $month^{-1}$ in the wet and dry season respectively during a 15-yr rotation; light-saturated photosynthetic rate of tropical acacias has also been found to be greater in the wet than dry season (Eyles et al., 2015). The VN sites were the most severely affected ($f_{\mathrm{ASW}} = 0.47$). This may be related to the greater slopes leading to more run-off and shallower soils than those present in the other regions (Sam, 2001) which may have resulted in lower levels of *ASW* than could be detected at a monthly time-step (Almeida and Sands, 2016). In the wet season, available water consistently had little effect on growth (f_{ASW} ⩾0.95). Soil water availability during the wet season has been found previously not to be a factor limiting the growth and physiological performance of plantations in the tropics (Franco and Lüttge, 2002).

Temperature was also a limiting factor for growth; its effect was greater in the dry than wet season, and in the north than the south, and intermediate but similar in the two central regions. This pattern conforms to the distribution of mean monthly air temperature which was between 3 and 6 °C lower at the sites in north than south; the low minimum temperatures in the winter in the north resulted in the lowest value of f_T (=0.51). It is not clear why sites in the north are also limited by temperature in the wet season, but this may be associated with the frequent occurrence of temperatures that frequently exceed T_{max} (Lap, 1999). Kha (2003) has suggested that the absence of low temperatures in the south results in more favourable conditions for the growth of acacias. In this study T_{min} and T_{max} were set at 16 °C and 34 °C based on the minimum and maximum monthly temperatures recorded across the regions during the study period and the long-term monthly temperature for 1970 – 2005. The mean monthly temperature in the study regions ranged from 22 – 28.6 °C and T_{opt} was set at 23 °C, a figure consistent with previous studies that sought to identify the climatic requirements of *Acaci*a species in Vietnam (Nghia, 1996; Sein and Mitlöhner, 2011). The pattern of f_{VPD} and its effect on growth was similar to that of f_T but within a region, its value was similar in both the wet and dry seasons. Its primary effect is the limitation of tree growth because of stomatal closure (Almeida et al., 2007).

There were large differences in the chemical properties of the soils which were dominated by Acrisols and Ferralsols, which have deeply weathered acid profiles, and low cation exchange capacity, clay content, and natural fertility (Sang et al., 2013; Dong et al., 2014). Growth differences between regions were linked in part to *FR* and f_{FR}. The VS sites had the highest *FR* (0.7 – 0.8) and f_{FR} (= 0.9) which were associated with the highest levels of SOC, TN and for most sites, K^+, Mg^{2+} and Ca^{2+}. Conversely, VSC which had the lowest *FR* and f_{FR} had the lowest SOC and TN. The strong positive correlation between *FR* and SOC, K^+ and Ca^{2+} (R^2 = 0.91, p<0.0001) coincides with findings from studies in eucalypt plantations in Brazil (Stape et al., 2004) and Spain (Vega-Nieva et al., 2014), where the relationships between *FR* and basic cations were also found. In acid soils, the calcium content plays a role in the assimilation of other nutrients by regulating pH and modifying microbial activity (Sam et al., 2006), hence its correlation with *FR*. Stape et al. (2004) also predicted *FR* from a relationship based on soil K^+ as well as cation exchange capacity and available P for *E. grand*is × *urophylla* plantations in Brazil, which can respond strongly fertilization in K-deficient soils (Gonçalves et al., 2008; Laclau et al., 2009)., 2009). And for hybrid pine plantations, there is a positive relationship between surface SOC and exchangeable K^+ (R^2 = 0.81) and Ca^{2+} (R^2 = 0.5) (Smith et al., 2008). Thus SOC's importance may be associated with the capacity of low levels of cations in these soils to drive fertility. The absence of significant effects of soil texture, pH_{H_2O}, pH_{KCl}, avail. P and TN with *FR* may be attributed to the tolerance of tropical acacias to degraded soils and their ability to fix atmospheric N_2 (Cole et al., 1996; Turnbull et al., 1997; McNamara et al., 2006). It is possible that soil fertility will change through a rotation (Fontes et al., 2006; Almeida et al., 2010a); however, to model these changes, specific experiments would be required.

In our study, *FR* was held constant since no fertilizer had been applied during the rotation.

However, it is well known that nitrogen fixing species (including *A.* hybrid) can have a strong influence on the nutrient availability and cycling within plantations, and not just nitrogen but also other nutrients as well (Binkley and Giardina, 1997; Forrester et al., 2006). Ideally, it should be estimated by calibrating the model against data from a fertiliser trial (Stape, 2002). However, such information is often not available, and thus FR may need to be treated as a tunable parameter until a suitable single measure of soil fertility is developed. Therefore, future refinements that enable *FR* to vary through time would likely improve 3-PG predictions in *Acacia* plantations across Vietnam.

3.4.4. Sensitivity analysis

The parameters n_{S}, T_{opt}, Y and $\alpha_{\mathrm{C}x}$ were the most sensitive for the six selected model outputs. Previous studies have shown that T_{opt}, Y and $\alpha_{\mathrm{C}x}$ are the most sensitive parameters affecting prediction of W_{stem} and W_{foliar} (Almeida et al., 2004b; Xenakis et al., 2008), and n_{S}, Y, T_{opt}, p_{20}, $\gamma_{\mathrm{F}x}$, σ_1 and $\alpha_{\mathrm{C}x}$ for prediction of *LAI* (Almeida et al., 2004b; Esprey et al., 2004). The site-dependent parameters T_{max}, T_{min}, as well as T_{opt} generally show moderate to high sensitivity when using the model because of their importance in the conversion of light to biomass, and therefore must be accurately set if 3-PG is to be applied across a wide range of site climates (Esprey et al., 2004) as was the case in this study. Interestingly, T_{opt} is not commonly measured where 3-PG has been applied (Xenakis et al., 2008), though it can be derived from a good understanding of the natural distribution and adaptation to the region of the species being considered (Almeida et al., 2010a; González-García et al., 2016).

The time-dependence of parameter sensitivities influences model predictions (Song et al., 2013) and running the sensitivity analysis at age 7 and 15 year confirmed this expectation. Most studies that have applied sensitivity analysis to 3-PG found that n_S is the most sensitive parameter that has an increasing effect on *DBH*, W_{foliar} and *LAI*, in particular towards the end of the rotation, and α_{Cx} on all growth variables because of changes in photosynthetic capacity at leaf level as the stand ages (Almeida et al., 2004b). Although not all parameters strongly affect the outputs as the trees age, stand growth decreases, and small changes in their value may have a greater impact (Song et al., 2013).

The results demonstrate that sensitivity analysis effectively quantifies the relative importance of the parameter to the outputs and the dependency with the age of the stand, as found in (Song et al., 2013). Our study shows that sensitivity analysis contributes to the optimisation of measurements and helps to ensure the adequate parameterisation, calibration and validation of 3-PG.

3.5. Conclusions

3-PG was successfully calibrated and validated to predict the growth of *A.* hybrid plantations, and for the first time, to quantify its potential productivity for a range of climates and soils in Vietnam. Using a single set of parameters, the model accurately predicted growth and identified limiting factors for different regions, though it was more accurate in predicting productivity in the North and North Central Coast than the South and South Central Coast regions. Available soil water (*ASW*) was the factor most limiting for growth, though in the dry season only; temperature and *VPD* also affected growth but less so than *ASW*. The estimation of *FR* demonstrated the importance of basic cations Ca^{2+} and K^{+} in the expression of soil fertility, and the role that SOC may play in their mobilisation where cation levels are low. Sensitivity analysis showed the effect of each parameter on model output as well as the variability of the main outputs at two different stand ages and identified the most important parameters for which to prioritise measurements. Although further characterisation of these highly variable soils is an important requirement for the application of the model at large scales, in its current form it can provide all the necessary information for growers at local and regional levels to manage *A*. hybrid plantations for wood products in Vietnam.

Appendices

Appendix Table 3.1 List of parameters for *A.* hybrid used within the 3-PG model.

Meaning/comments	Symbol	Units	Values	Value source
Biomass partitioning and turnover				
Allometric relationships & partitioning				
Foliage:stem partitioning ratio at *DBH* = 2 cm	p_2	-	0.75	Estimated from observed data
Foliage:stem partitioning ratio at *DBH* = 20 cm	p_{20}	-	0.1	Estimated from observed data
Constant in the stem mass and diameter relationship	a_{S}	-	0.0835	Observed
Power in the stem mass and diameter relationship	n_{S}	-	2.6171	Observed
Maximum fraction of *NPP* to roots	$\eta_{\mathrm{R}x}$	-	0.6	Almeida et al. (2004)
Minimum fraction of *NPP* to roots	$\eta_{\mathrm{R}n}$	-	0.1	Almeida et al. (2004)
Litterfall & root turnover				
Maximum litterfall rate	$\gamma_{\mathrm{F}x}$	month^{-1}	0.03	Observed
Litterfall rate at t = 0	γ_{F0}	month^{-1}	0.001	Sang (2008)
Age at which litterfall rate $= \frac{1}{2}(\gamma_{\mathrm{F0}} + \gamma_{\mathrm{Fx}})$	$t_{\gamma\mathrm{F}}$	month^{-1}	12	Sands and Landsberg (2002)
Average monthly root turnover rate	γ_{R}	month^{-1}	0.015	Sang (2008)
NPP & conductance modifiers				
Temperature modifier				
Minimum temperature for growth	T_{min}	°C	16	Table 1; Nghia, 1996
Optimum temperature for growth	T_{opt}	°C	23	Table 1; Nghia, 1996
Maximum temperature for growth	T_{max}	°C	34	Table 1; Nghia, 1996
Frost modifier				
Days production lost per frost day	d_{F}	days	0	Sang (2008)
Soil water modifier				
Moisture ratio deficit for $f_\theta = 0.5$	c_θ	-	0.5	Landsberg and Waring (1997)
Power of moisture ratio deficit	n_θ	-	5	Landsberg and Waring (1997)

Meaning/comments	Symbol	Units	Values	Value source
Atmospheric CO_2 modifier				
Value of modifier of quantum efficiency at 700 ppm	$f_{C\alpha 700}$	-	1.4	Almeida and Sands (2015)
Value of modifier of canopy conductance at 700 ppm	f_{Cg700}	-	0.7	Almeida and Sands (2015)
Fertitlity effects				
Value of m when *FR* = 0	m_0	-	0	Almeida and Sands (2015)
Value of f_N when *FR* = 0	f_{N0}	-	0.6	Almeida and Sands (2015)
Power of (1-*FR*) in f_N	f_{Nn}	-	1	Almeida and Sands (2015)
Age modifier				
Maximum stand age used in age modifier	t_x	years	30	Sang (2008)
Power of relative age in function for f_{age}	n_{age}	-	4	Almeida and Sands (2015)
Relative age to give f_{age} = 0.5	r_{age}	-	0.95	Almeida and Sands (2015)
Stem mortality & self-thinning				
Mortality rate for large t	γ_{Nx}	% year^{-1}	0	Almeida and Sands (2015)
Seedling mortality rate (t = 0)	γ_{N0}	% year^{-1}	0	Almeida and Sands (2015)
Age at which mortality rate has median value	$t_{\gamma N}$	years	0	Almeida and Sands (2015)
Shape of mortality response	$n_{\gamma N}$	-	1	Almeida and Sands (2015)
Maximum tree stem mass for 1000 trees ha^{-1}	w_{Sx1000}	kg tree^{-1}	300	Almeida and Sands (2015)
Power in self-thinning rule	n_N	-	1.5	Almeida and Sands (2015)
Fraction mean single-tree foliage biomass lost per dead tree	m_F	-	0	Almeida and Sands (2015)
Fraction mean single-tree root biomass lost per dead tree	m_R		0.2	Almeida and Sands (2015)
Fraction mean single-tree stem biomass lost per dead tree	m_S		0.2	Almeida and Sands (2015)
Canopy structure and processes				
Specific leaf area				
Specific leaf area at stand age 0	σ_0	m^2 kg^{-1}	12.5	Observed
Specific leaf area for mature aged stands	σ_1	m^2 kg^{-1}	4	Observed
Age at which specific leaf area = $\frac{1}{2}(\sigma_0 + \sigma_1)$	t_σ	years	2.5	Estimated from observed data

Meaning/comments	Symbol	Units	Values	Value source
Light interception				
Extinction coefficient for absorption of *PAR* by canopy	k	-	0.5	Almeida et al. (2004)
Age at canopy cover	t_{c}	years	1.5	Observed
Maximum proportion of rainfall evaporated from canopy	I_{x}	-	0.15	Almeida et al. (2004)
LAI for maximum rainfall interception	$L_{\mathrm{I}x}$	-	0	Almeida and Sands (2015)
Production and respiration				
Maximum canopy quantum efficiency	$\alpha_{\mathrm{C}x}$	mol mol^{-1}	0.068	Almeida et al. (2004)
Ratio *NPP*/*GPP*	Y	-	0.47	Almeida and Sands (2015)
Conductance				
Minimum canopy conductance	$g_{\mathrm{C}x}$	m s^{-1}	0	Almeida and Sands (2015)
Maximum canopy conductance	$g_{\mathrm{C}x}$	m s^{-1}	0.0208	Observed
LAI for maximum canopy conductance	$L_{\mathrm{C}x}$	-	3.33	Almeida and Sands (2015)
Defines stomatal response to *VPD*	k_{g}	kPa^{-1}	0.05	Almeida et al. (2004)
Canopy boundary layer conductance	g_{B}	m s^{-1}	0.2	Almeida and Sands (2015)
Wood and stand properties				
Branch and bark fraction				
Branch and bark fraction at stand age 0	p_{B0}	-	0.7	Observed
Branch and bark fraction for mature aged stands	p_{B1}	-	0.1	Observed
Age at which $\mathrm{p_B} = \frac{1}{2}(\mathrm{p_{B0}} + \mathrm{p_{B1}})$	$t_{p\mathrm{B}}$	years	2	Estimated from observed data
Basic density				
Minimum basic density for young trees	ρ_{min}	t m^{-3}	0.455	Observed
Maximum basic density for older trees	ρ_{max}	t m^{-3}	0.542	Observed
Age at which $\rho = \frac{1}{2}(\rho_{\mathrm{min}} + \rho_{\mathrm{max}})$	t_{ρ}	years	4	Estimated from observed data
Conversion factors				
Intercept of net-versus-solar radiation relationship	Q_{a}	W m^{-2}	-8.85	Almeida and Sands (2015)
Slope of net-versus-solar radiation relationship	Q_{b}	-	0.8	Almeida and Sands (2015)
Molecular weight of dry matter	*gDM_mol*	gDM mol^{-1}	24	Almeida and Sands (2015)
Conversion of solar radiation to *PAR*	*molPAR_MJ*	mol MJ^{-1}	2.3	Almeida and Sands (2015)

Appendix 3.2 Results of the sensitivity analysis of 21 parameters on selected 3-PG outputs.

Parameter*	Variation (%)	7 years						15 years					
		DBH	W_{stem}	W_{foliar}	W_{root}	*LAI*	*WUE*	*DBH*	W_{stem}	W_{foliar}	W_{root}	*LAI*	*WUE*
High sensitivity													
n_S	-20	85.1	-4.1	-39.4	-14.1	-38.7	9.4	92.7	-12.3	-53.2	-26.2	-51.9	2.9
	-10	32.0	-1.1	-18.9	-5.8	-18.9	5.9	35.7	-3.0	-26.5	-9.9	-25.6	1.5
	+10	-20.4	0.8	17.6	4.7	17.6	-5.3	-22.8	0.4	23.2	5.9	23.3	-5.2
	+20	-34.1	2.2	36.7	9.1	36.0	-1.6	-37.5	2.0	45.5	11.3	46.1	-10.4
T_{opt}	-20	-13.6	-33.9	-28.2	-37.8	-26.1	-21.1	-13.7	-34.2	-30.8	-39.3	-27.8	-25.8
	-10	-6.0	-16.2	-13.0	-17.8	-11.8	-8.7	-5.8	-15.6	-13.6	-18.1	-12.1	-11.0
	+10	4.5	13.3	9.9	14.5	8.7	5.9	7.3	9.7	9.1	11.6	8.2	6.7
	+20	7.4	22.3	16.6	24.3	14.2	9.5	13.2	15.4	14.3	18.9	12.7	10.8
Y	-20	-9.2	-24.1	-18.7	-25.4	-19.1	-15.2	-9.4	-24.5	-20.8	-26.6	-20.2	-18.8
	-10	-4.5	-12.4	-9.2	-12.9	-9.5	-7.3	-4.5	-12.3	-10.0	-13.3	-9.8	-9.1
	+10	4.5	13.2	9.0	13.5	9.3	6.8	7.5	10.0	8.5	10.9	8.8	7.9
	+20	8.7	26.8	17.9	27.2	18.5	13.6	16.7	18.8	15.3	20.8	16.1	15.7
σ_1	-20	-1.5	-4.1	-4.1	-6.3	-23.1	7.2	-2.2	-6.2	-9.1	-10.9	-26.5	1.5
	-10	-0.6	-1.8	-1.7	-2.8	-11.4	3.6	-0.9	-2.5	-3.8	-4.7	-13.1	1.2
	+10	0.5	1.4	1.1	2.4	11.0	-3.4	0.5	1.5	1.9	3.4	12.3	-2.7
	+20	1.1	3.0	2.5	4.7	22.5	-5.2	1.1	3.1	3.4	6.4	24.5	-5.5
α_{Cx}	-20	-9.2	-23.9	-19.1	-25.9	-19.5	-16.2	-9.8	-25.4	-22.1	-27.9	-21.4	-19.9
	-10	-4.4	-12.0	-9.3	-12.9	-9.6	-7.7	-4.6	-12.6	-10.8	-13.9	-10.4	-9.7
	+10	4.3	12.7	9.3	13.4	9.6	7.2	4.3	12.7	10.4	13.9	10.0	9.2
	+20	8.5	25.9	18.2	27.1	18.7	14.0	9.6	24.2	19.4	26.6	19.1	17.3
γ_{Fx}	-20	0.8	2.4	19.6	3.9	18.4	-5.6	1.0	3.0	31.9	7.3	31.9	-7.2
	-10	0.4	1.2	9.2	1.9	8.7	-2.7	0.6	1.6	14.6	3.8	14.7	-3.2
	+10	-0.5	-1.3	-8.3	-2.0	-8.0	2.5	-0.8	-2.2	-13.5	-4.3	-13.1	1.2
	+20	-1.0	-2.8	-16.0	-4.1	-15.5	4.9	-1.7	-4.8	-25.3	-9.0	-24.4	1.5
p_{20}	-20	-0.3	-0.7	-14.9	-4.2	-14.8	4.7	-0.8	-2.2	-22.5	-7.8	-21.6	1.6
	-10	-0.1	-0.2	-7.2	-1.9	-7.1	2.2	-0.3	-0.8	-11.0	-3.4	-10.6	1.1
	+10	0.1	0.2	6.8	1.7	6.7	-2.1	0.1	0.2	9.8	2.7	9.9	-2.2

	+20	0.1	0.3	13.4	3.3	13.2	-4.1	0.1	0.2	19.2	4.8	19.3	-4.3

Parameter*	Variation (%)	7 years						15 years					
		DBH	W_{stem}	W_{foliar}	W_{root}	*LAI*	*WUE*	*DBH*	W_{stem}	W_{foliar}	W_{root}	*LAI*	*WUE*
T_{max}	-20	-7.8	-20.5	-16.5	-22.3	-15.2	-11.6	-7.5	-19.9	-17.2	-22.5	-15.4	-14.0
	-10	-2.7	-7.4	-5.7	-7.9	-5.2	-4.0	-2.5	-7.0	-5.8	-7.9	-5.3	-4.7
	+10	1.7	4.9	3.6	5.2	3.3	2.5	1.8	4.4	3.5	4.9	3.2	2.7
	+20	2.9	8.4	6.1	8.9	5.7	4.3	4.2	6.7	5.8	7.6	5.5	4.5
T_{min}	-20	4.2	12.4	8.9	12.7	8.8	5.5	6.9	9.4	8.3	10.3	8.4	6.1
	-10	2.3	6.8	4.9	6.9	4.9	3.1	3.1	5.7	4.8	6.1	4.8	3.4
	+10	-2.9	-7.9	-6.0	-8.2	-5.9	-4.0	-2.8	-7.8	-6.3	-8.3	-6.1	-4.9
	+20	-6.3	-16.8	-13.3	-17.6	-13.2	-9.7	-6.3	-16.8	-14.3	-18.2	-13.6	-11.8
g_{Cx}	-20	3.4	9.8	6.6	6.2	6.5	16.4	4.9	7.4	4.0	3.9	4.6	15.3
	-10	1.6	4.6	3.1	3.0	3.1	7.4	1.5	4.1	2.1	2.5	2.3	7.1
	+10	-1.5	-4.2	-3.0	-2.8	-3.0	-6.2	-1.4	-3.9	-2.4	-2.5	-2.3	-6.6
	+20	-2.8	-7.8	-5.6	-5.3	-5.6	-11.6	-2.7	-7.4	-4.7	-4.9	-4.5	-12.3
k	-20	-5.3	-14.2	-10.4	-14.7	-10.7	-8.5	-5.4	-14.5	-12.9	-16.1	-12.4	-12.1
	-10	-2.3	-6.4	-4.5	-6.6	-4.6	-3.7	-2.4	-6.5	-5.7	-7.3	-5.5	-5.4
	+10	1.9	5.5	3.6	5.5	3.7	2.9	2.4	5.0	4.4	5.6	4.4	4.1
	+20	3.5	10.1	6.6	10.1	6.8	5.2	5.8	8.3	7.9	9.4	8.0	7.5
L_{Cx}	-20	-1.6	-4.4	-4.2	-2.9	-3.8	-13.9	-2.5	-6.8	-6.3	-5.3	-6.0	-14.7
	-10	-0.8	-2.4	-2.3	-1.6	-2.0	-7.2	-1.2	-3.4	-2.9	-2.5	-2.8	-7.2
	+10	1.0	2.7	2.2	1.8	2.0	7.0	1.1	3.2	2.1	2.2	2.2	6.4
	+20	1.9	5.5	4.2	3.6	3.8	13.8	3.0	5.6	3.7	3.5	4.1	12.3
FR	-20	-4.4	-12.0	-8.5	4.4	-8.7	-2.9	-6.5	-9.9	-8.3	6.6	-8.5	-3.9
	-10	-2.2	-6.1	-4.2	2.0	-4.4	-1.4	-4.3	-4.1	-3.9	3.9	-4.1	-1.9
	+10	2.1	6.0	4.0	-1.7	4.2	1.3	4.2	4.0	3.4	-3.3	3.6	1.9
	+20	4.0	11.8	8.0	-3.3	8.2	2.7	8.4	7.9	6.4	-6.1	6.8	3.9
f_{N0}	-20	-3.4	-9.3	-6.9	-9.7	-7.0	-5.5	-3.3	-9.2	-7.4	-9.9	-7.3	-6.7
	-10	-1.7	-4.7	-3.3	-4.9	-3.4	-2.7	-1.6	-4.6	-3.6	-4.9	-3.6	-3.3
	+10	1.7	4.8	3.3	5.0	3.4	2.6	1.8	4.4	3.4	4.8	3.4	3.0
	+20	3.4	9.8	6.7	10.1	7.0	5.2	5.3	7.8	6.5	8.4	6.7	5.9
η_{Rn}	-20	3.4	10.0	7.7	-9.5	7.8	-1.7	3.7	10.7	9.2	-8.7	8.9	-0.1
	-10	1.6	4.7	3.7	-4.4	3.8	-0.8	1.8	5.1	4.4	-4.0	4.3	0.0
	+10	-1.6	-4.3	-3.4	3.9	-3.5	0.7	-1.7	-4.7	-4.1	3.4	-4.0	-0.1
	+20	-3.0	-8.4	-6.7	7.3	-6.8	1.3	-3.3	-9.2	-7.9	6.2	-7.7	-0.2

Parameter*	Variation (%)	7 years						15 years					
		DBH	W_{stem}	W_{foliar}	W_{root}	*LAI*	*WUE*	*DBH*	W_{stem}	W_{foliar}	W_{root}	*LAI*	*WUE*
Low sensitivity													
t_{σ}	-20	-0.8	-2.2	-1.0	-3.5	-3.1	0.9	-0.3	-0.9	0.2	-0.6	0.2	0.0
	-10	-0.5	-1.5	-0.7	-2.0	-2.2	0.7	-0.2	-0.6	0.2	-0.3	0.2	0.0
	+10	0.7	2.1	1.0	2.5	3.7	-1.1	0.3	0.9	-0.2	0.4	-0.2	0.0
	+20	1.4	4.1	2.0	4.9	8.8	-2.8	0.6	1.7	-0.4	0.9	-0.4	0.1
a_{S}	-20	8.0	-0.5	-6.2	-2.0	-6.3	2.0	7.9	-0.6	-7.2	-2.5	-7.1	0.8
	-10	3.7	-0.2	-2.9	-0.9	-3.0	0.9	3.7	-0.2	-3.3	-1.1	-3.3	0.5
	+10	-3.2	0.2	2.7	0.9	2.7	-0.9	-3.2	0.2	3.0	1.0	3.0	-0.6
	+20	-6.1	0.5	5.3	1.7	5.4	-1.7	-6.1	0.4	5.7	1.8	5.8	-1.2
k_{g}	-20	2.4	6.8	4.9	2.9	4.8	-0.5	3.4	6.0	5.4	2.4	5.6	-0.2
	-10	1.1	3.3	2.4	1.4	2.3	-0.2	1.2	3.3	2.7	1.6	2.8	-0.1
	+10	-1.2	-3.4	-2.6	-1.5	-2.6	0.3	-1.2	-3.5	-3.3	-1.8	-3.1	-0.6
	+20	-2.4	-6.7	-5.3	-3.1	-5.4	0.7	-2.5	-7.0	-6.7	-3.8	-6.1	-1.4
p_{2}	-20	-0.6	-1.8	-7.3	-3.6	-7.9	2.7	-0.3	-0.9	-2.6	-1.7	-2.8	0.6
	-10	-0.3	-0.9	-3.5	-1.7	-3.8	1.3	-0.2	-0.5	-1.2	-0.8	-1.3	0.3
	+10	0.2	0.7	3.2	1.5	3.5	-1.3	0.1	0.4	1.1	0.7	1.2	-0.3
	+20	0.4	1.2	6.2	2.7	6.7	-2.4	0.2	0.6	2.2	1.3	2.3	-0.5
η_{Rx}	-20	0.9	2.5	1.6	-4.9	1.7	-0.5	0.8	2.3	1.7	-4.8	1.7	-0.2
	-10	0.4	1.1	0.8	-2.2	0.8	-0.2	0.4	1.1	0.8	-2.2	0.8	-0.1
	+10	-0.3	-1.0	-0.7	1.9	-0.7	0.2	-0.3	-0.9	-0.7	1.8	-0.7	0.1
	+20	-0.6	-1.8	-1.2	3.6	-1.3	0.4	-0.6	-1.7	-1.2	3.4	-1.2	0.1
σ_{0}	-20	-0.8	-2.3	-0.4	-3.0	-1.1	0.3	-0.3	-0.9	0.3	-0.4	0.3	-0.1
	-10	-0.5	-1.3	-0.3	-1.5	-0.7	0.2	-0.2	-0.5	0.2	-0.2	0.2	0.0
	+10	0.6	1.8	0.5	1.7	0.9	-0.3	0.3	0.7	-0.2	0.3	-0.2	0.0
	+20	1.4	3.9	1.1	3.6	2.1	-0.6	0.6	1.6	-0.5	0.6	-0.5	0.1

* See Appendix 3.1 for meanings of parameter.


Root depth and biomass

Root collection


Litterfall

Leaf area index


Stomatal conductance

Weight branches and leaves

Data collection in three calibration sites for 3-PG model (Photo taken: Trieu Thai Hung, 2012).

CHAPTER 4

MAXIMISING GROWTH AND LOG SIZE FROM *ACACIA* HYBRID PLANTATIONS IN VIETNAM

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CHAPTER 4. MAXIMISING GROWTH AND SAWLOG PRODUCTION FROM *ACACIA* HYBRID PLANTATIONS IN VIETNAM

Abstract

The growth responses of *Acacia* hybrid plantations to a range of thinning and fertiliser-at-thinning treatments at six experimental trials across Vietnam were quantified to evaluate and optimise sawlog production. Different experimental thinning regimes reducing initial stockings of 2000, 1667 and 1111 trees ha^{-1} to 1333, 1000, 900, 667, 600 or 450 trees ha^{-1} at varying ages from 2 to 5.6 years were applied. Tree diameter (*DBH*) and stand volume (*SV*) responses to thinning were greater in the south than in north and south central coast. Application of fertiliser at thinning increased *DBH* and *SV*, compared with the unfertilised treatment. Early thinning to 450 or 600 trees ha^{-1} resulted in the greatest *DBH* for all diameter classes with a greater proportion of larger diameter logs. Thinning to 900 or 1000 trees ha^{-1} resulted in low diameter increments but higher yields of small sawlogs and total *SV* than higher intensity thinnings. The 3-PG process-based model was applied to predict *DBH* and *SV* for all silvicultural treatments and advanced ages. Modelling results suggested that *Acacia* hybrid plantations managed for large sawlog production would benefit from rotation length to at least 5 – 7 years in the south and south central coast and 6 – 10 years in north Vietnam.

Keywords: Acacias, productivity, sawlogs, silvicultural practices, 3-PG model

4.1. Introduction

In Vietnam, more than 1.1 Mha of *Acacia* plantations are grown primarily for pulpwood (AGROINFO, 2014) but high volatility in domestic and world pulp prices and the need for product diversification has increased interest in growing *Acacia*, particularly clonal *A.* hybrid (*A. mangium* × *A. auriculiformis*), plantations for sawlog products (MARD, 2015). These plantations, of which half of the area are owned by smallholders, are commonly established at 1111 – 2500 trees ha^{-1} and managed on a rotation length of 5 – 8 years without thinning (Beadle et al., 2015; Nambiar et al., 2015). Historically, plantations systems grown for sawlog production usually require at least one thinning to manage stand stocking and increase the diameter of retained trees (Beadle et al., 2013a). Optimum thinning regimes have been tested and developed for a range of fast-growing plantation species including various temperate and tropical *Eucalyptus* spp. (Medhurst and Beadle, 2001; Smith and Brennan, 2006; Cassidy et al., 2012). In contrast, there is a paucity of published research on thinning for fast-growing tropical *Acacia* spp. (Beadle et al., 2013a; Huong et al., 2016).

In eucalypt plantations, intensity and timing of thinning arguably have the most impact on product recovery (Smith and Brennan, 2006; Glencross et al., 2011; Cassidy et al., 2012; Forrester et al., 2013a). In particular, early-age thinning has been shown to improve log size without increasing the vulnerability of a stand to wind throw as well maintain the benefits realised from high early growth rates across the rotation (Medhurst and Beadle, 2001; Smith and Brennan, 2006; Cassidy et al., 2012). For tropical acacia plantations in which stands reach canopy closure at age 2 years, there remains uncertainties on the intensity and timing of thinning but likely, it will need to be applied at early rather at later ages to reduce the risk of intraspecific competition. In a recent study comparing thinning treatments of *A.* hybrid in southern Vietnam, concluded that thinning from 1111 trees ha^{-1} to 600 trees ha^{-1} at age 2 years or to 833 trees ha^{-1} at age 3 years would produce the highest diameter sawlogs. Early thinning of a 2.5-year-old *A.* hybrid plantation from 1000 to 600 but not 450 and 300 trees ha^{-1} was shown to rapidly realise sawlog values (defined as log DBH >15 cm in small-end diameter) in central Vietnam (Beadle et al., 2013a). The findings from these two studies suggest that for plantations with initial stocking rate of 1000-1100 trees ha^{-1}, higher diameter classes can be obtained by managing thinning age and intensity, however there is little information on the effect of thinning age and intensity for plantations with an initial stocking higher than 1600 tree ha^{-1} growing across Vietnam.

Thinning in combination with fertilisation is widely practised for many forest plantation species (Miller and Tarrant, 1983; Valinger et al., 2000; Mäkinen et al., 2005; Forrester et al., 2012). However, in Vietnam, many growers, particularly smallholders, use little or no inorganic fertiliser and/or manure at establishment due to the costs of fertiliser and associated labour (Son, 2006; Dung et al., 2013). This is in contrast to the recommendations from other studies, which demonstrate a higher requirement for phosphorus (P) in leguminous tree species such as *Acacia* compared to non-leguminous tree species (Sprent, 1999). Other studies have shown that application of P fertilizer alone improved early growth rates for *Acacia* plantations, compared to no fertiliser controls, especially on low fertility sites (Mendham et al., 2010; Beadle et al., 2013b; Dung et al., 2013). These findings suggest that the benefits from thinning may be enhanced with P fertiliser in *A.* hybrid plantations but this remains unclear.

The aim of this study was, using both empirical mensuration and process-based modelling, to estimate the wood yields of log product sizes and to determine rotation length for producing sawlog under different thinning and fertiliser application practiced in *A*. hybrid plantations (with initial stand stocking varying from 1111 to 2000 stems ha^{-1}) across Vietnam. The 3-PG model (Landsberg and Waring, 1997) has been parameterised and validated to quantify *A*. hybrid productivity in Vietnam (Hung et al., 2016b) but this is the first time it has been used to predict the potential yield of wood products in thinned stands of *Acacia* plantations. Thinning and fertilisation regimes were evaluated in relation to diameter growth rates, total volume and log sizes for different rotation lengths.

4.2. Materials and methods

4.2.1. Study area

The study area was composed of six experimental trials located in north (Tuyen Quang, Ba Vi-1, Ba Vi-2 and Ba Vi-3), south central coast (Binh Dinh) and south (Dong Nai) Vietnam. The sites represent a broad range of soils, topographies and climates under which *A.* hybrid is planted in Vietnam (Table 4.1). The study sites in north and south central coast are hilly (⩽15% slopes) compared to the flat sites in the south (⩽5% slopes). The climate across these sites is monsoon tropical with the monsoon pattern varying in duration and intensity (Lap, 1999). Meteorological variables such as mean monthly air temperature, daily solar radiation, and mean annual precipitation of each experimental site are presented in Table 4.1. Dry season (assumed as monthly precipitation < 40 mm) ranges from 3 to 4 months per year across sites (Hung et al., 2016b). The soils are mainly highly acidic and usually shallow (< 100 cm). The key soil properties in the top 10 cm soil depth are summarised in Table 4.1. In brief, they are clay loam or silty clay loam (clay 13.6 – 28.9%), pH_{H_2O} 3.4 – 5.7, soil organic carbon 1.1 – 2.7%, total soil N 0.04 – 0.16%, avail. P 1.8 – 11.1 mg kg^{-1}, exchangeable Ca 0.01 – 0.18 cmol kg^{-1}, K 0.07 – 0.12 cmol kg^{-1} and Mg 0.06 – 0.09 cmol kg^{-1} (Hung et al., 2016b).

The experimental plantations were established between 2006 and 2010. The slash was retained at Tuyen Quang, Ba Vi-1 and Dong Nai while the slash was ripped and burnt at Ba Vi-2, Ba Vi-3 and Binh Dinh prior to planting (Table 4.1). Across all trials, the planting hole size was 40 × 40 × 40 cm. Stocking at planting ranged from 1111 trees ha^{-1} up to 2000 trees ha^{-1} (Table 4.1). At planting, trees across all trials received basal N:P:K fertiliser and/or superphosphate (16 to 50 kg P ha^{-1}), which was spread at the bottom of the planting hole and then backfilled with soil. An additional 2 kg of cattle manure per tree was applied in Ba Vi-2 and Ba Vi-3 only. Either one *A*. hybrid clone or a mix of several clones (BV10, BV16, BV32, BV33, BV71, BV73 and BV75) were planted at each site. More details about the clones are detailed in Kha et al. (2012). Weeds were controlled by glyphosate (1.92 kg ha^{-1}) or hand-weeded twice per year for at least the first two years after planting. Tip pruning was applied to remove 50% of the length of potentially competing leaders and branches in the first year to produce a single leader. Lift pruning was undertaken to 2.5 m above ground before thinning to reduce branch competition.

Table 4.1 Properties of six experimental trials including location, soil, climate, site management history and experimental design in Vietnam (See Appendix Figure 4.1 for location of the six experimental trials).

	Tuyen Quang	Ba Vi-1	Ba Vi-2	Ba Vi-3	Binh Dinh	Dong Nai
Region	North	North	North	North	South central	South
Latitude (N)	21.7	21.1	21.1	21.1	13.8	11.3
Longitude (E)	105.2	105.3	105.3	105.3	108.9	106.8
Altitude (m a.s.l)	34	35	35	35	106	100
Soil type	Ferralic Acrisols	Ferralic Acrisols	Ferralic Acrisols	Ferralic Acrisols	Rhodic Ferralsols	Ferralic Acrisols
Soil texture	Clay loam	Clay loam	Clay loam	Clay loam	Loamy sand	Sandy clay loam
Clay (%)	22.5	28.9	24.4	24.4	23.4	13.6
pH_{H2O}	4.4	3.4	3.7	3.7	5.7	5.4
SOC (%)	1.7	2.7	1.6	1.6	1.1	2.0
TN (%)	0.11	0.16	0.15	0.15	0.04	0.14
Avail. P (mg kg^{-1})	4.9	1.8	3.9	3.9	NA	11.1
Ex-Ca (cmol kg^{-1})	0.18	0.06	0.01	0.07	0.04	0.04
E_X-K (cmol kg^{-1})	0.07	0.12	0.12	0.08	0.07	0.07
Ex-Mg (cmol kg^{-1})	0.09	0.08	0.06	0.08	0.06	0.06
Mean annual T_{max}/ T_{min}/ Temp. (°C)	28.0/16.0/22.0	28.8/20.7/24.7	28.8/20.7/24.7	28.8/20.7/24.7	31.0/24.8/27.9	31.4/23.7/27.6
Mean annual rainfall (mm)	1650	1630	1630	1630	1664	1180
Mean annual radiation (MJ m^{-2} day^{-1})	14.3	15.5	15.5	15.5	15.0	18.9
N° months with rainfall < 40 mm (month)	4	3	3	3	3-4	4
Site preparation	Slash retention	Slash retention	Slash burned and ripped	Slash burned and ripped	Slash burned and ripped	Slash retention
Stocking at planting (trees ha^{-1})	1111	1111	1667	1667	2000	1111
Planting time	July 2009	June 2009	September 2006	September 2006	July 2009	August 2010
Fertiliser at planting (N:P:K kg ha^{-1})	17.8:50: 8.9	17.8:50: 8.9	8.3:16.7:5	16.6: 33.3:10	16:16:8	17.8:50: 8.9
Experimental design						
Gross (net) plot size (m^2)	576 (320)	576 (324)	432 (252)	432 (252)	490 (300)	576 (324)
Replicates	3	3	4	4	4	3
Trees per net plot	36	36	42	42	60	36
Spacing (m)	3 × 3	3 × 3	3 × 2	3 × 2	2.5 × 2.0	3 × 3
Clones	1	4	1	7	4	1

4.2.2. Experiment design and treatments

The experiments at each trial site were designed as randomized complete blocks, with 3 – 5 replicates. There were a total of 157 sample plots, each consisting of a minimum of 36 trees. Each plot had a double row of buffer trees along the plot boundaries that received the same thinning and fertiliser at thinning treatments. Gross plot sizes ranged from 432 to 630 m^2 while net plot sizes (the measured plot) ranged from 252 to 367.5 m^2.

Thinning treatments included various thinning intensities (thinning from 2000, 1667 and 1111 trees ha^{-1} to 1333, 1000, 900, 600, 667 or 450 trees ha^{-1}) and thinning ages (2 to 5.6 yr) (Table 4.2). Thinning to 600 trees ha^{-1} at age 2-yr were examined at Tuyen Quang, Ba Vi-1 and Dong Nai. Progressive thinning treatment to 800 trees ha^{-1} at age 2 yr and then 600 trees ha^{-1} at age 3 yr was examined at Dong Nai. The effects of thinning intensity at age ⩾3 yr on growth responses were evaluated at Ba Vi-2, Ba Vi-3, Binh Dinh and Dong Nai. Combinations of thinning intensity and time of thinning (thinned at different tree ages: 3.6, 4.6 and 5.6 yr) were tested at Ba Vi-3. At Tuyen Quang, Ba Vi-1 and Ba Vi-2, for each thinning intensity, three fertiliser treatments were immediately applied after thinning including 1) no additional fertiliser (F_0), 2) 17.8, 50 and 8.9 kg ha^{-1} of N, P and K fertiliser, respectively (F_1), and 3) 17.8, 50 and 8.9 kg ha^{-1} of N, P and K fertiliser, respectively, plus multi-element fertiliser (F_2). Further descriptions of the thinning and fertiliser treatments are available in Beadle et al. (2013a) and Dung et al. (2013).

Table 4.2 Description of thinning and fertiliser treatments applied across the six experimental trials. A fertility rating (*FR*) was used in 3-PG model and assigned for each treatment.

Trial (tree age)	Thinning intensity	Thinning code	Fertiliser at thinning (kg tree^{-1})	Fertiliser code	*FR*
Tuyen Quang	No thinning (1111 trees ha^{-1})	NT_{1111}	No fertiliser	F_0	0.30
(5.4 yr)	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	No fertiliser	F_0	0.30
	No thinning (1111 trees ha^{-1})	NT_{1111}	0.02 N, 0.05 P, 0.08 K	F_1	0.33
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	0.02 N, 0.05 P, 0.08 K	F_1	0.33
	No thinning (1111 trees ha^{-1})	NT_{1111}	0.02 N, 0.05 P, 0.08 K, 0.15 B*	F_2	0.33
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	0.02 N, 0.05 P, 0.08 K, 0.15 B	F_2	0.33
Ba Vi-1	No thinning (1111 trees ha^{-1})	NT_{1111}	No fertiliser	F_0	0.30
(5.9 yr)	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	No fertiliser	F_0	0.30
	No thinning (1111 trees ha^{-1})	NT_{1111}	0.02 N, 0.05 P, 0.08 K	F_1	0.33
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	0.02 N, 0.05 P, 0.08 K	F_1	0.33
	No thinning (1111 trees ha^{-1})	NT_{1111}	0.02 N, 0.05 P, 0.08 K, 0.15 B	F_2	0.33
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	0.02 N, 0.05 P, 0.08 K, 0.15 B	F_2	0.33
Ba Vi-2	No thinning (1667 trees ha^{-1})	NT_{1667}	No fertiliser	F_0	0.30
(7.4 yr)	Thinned to 600 trees ha^{-1} at age 3.6 yr	$T_{600/3.6}$	No fertiliser	F_0	0.30
	No thinning (1667 trees ha^{-1})	NT_{1667}	0.02 N, 0.05 P, 0.08 K	F_1	0.33
	Thinned to 600 trees ha^{-1} at age 3.6 yr	$T_{600/3.6}$	0.02 N, 0.05 P, 0.08 K	F_1	0.33
	No thinning (1667 trees ha^{-1})	NT_{1667}	0.02 N, 0.05 P, 0.08 K, 0.15 B	F_2	0.33
	Thinned to 600 trees ha^{-1} at age 3.6 yr	$T_{600/3.6}$	0.02 N, 0.05 P, 0.08 K, 0.15 B	F_2	0.33

Table 4.2 (***continuation***) Description of thinning and fertiliser treatments applied across the six experimental trials. A fertility rating (*FR*) was used in 3-PG model and assigned for each treatment.

Trial (tree age)	Thinning intensity	Thinning code	Fertiliser at thinning (kg tree^{-1})	Fertiliser code	*FR*
Ba Vi-3 (7.4 yr)	No thinning (1667 trees ha^{-1}) at age 3.6 yr	$NT_{1667/3.6}$	No fertiliser	F_0	0.50
	Thinned to 900 trees ha^{-1} at age 3.6 yr	$T_{900/3.6}$	No fertiliser	F_0	0.50
	Thinned to 600 trees ha^{-1} at age 3.6 yr	$T_{600/3.6}$	No fertiliser	F_0	0.50
	Thinned to 450 trees ha^{-1} at age 3.6 yr	$T_{450/3.6}$	No fertiliser	F_0	0.50
	No thinning (1667 trees ha^{-1}) at age 4.6 yr	$NT_{1667/4.6}$	No fertiliser	F_0	0.50
	Thinned to 900 trees ha^{-1} at age 4.6 yr	$T_{900/4.6}$	No fertiliser	F_0	0.50
	Thinned to 600 trees ha^{-1} at age 4.6 yr	$T_{600/4.6}$	No fertiliser	F_0	0.50
	Thinned to 450 trees ha^{-1} at age 4.6 yr	$T_{450/4.6}$	No fertiliser	F_0	0.50
	No thinning (1667 trees ha^{-1}) at age 5.6 yr	$NT_{1667/5.6}$	No fertiliser	F_0	0.50
	Thinned to 900 trees ha^{-1} at age 5.6 yr	$T_{900/5.6}$	No fertiliser	F_0	0.50
	Thinned to 600 trees ha^{-1} at age 5.6 yr	$T_{600/5.6}$	No fertiliser	F_0	0.50
	Thinned to 450 trees ha^{-1} at age 5.6 yr	$T_{450/5.6}$	No fertiliser	F_0	0.50
Binh Dinh (5.3 yr)	No thinning (2000 trees ha^{-1})	NT_{2000}	No fertiliser	F_0	0.60
	Thinned to 1333 trees ha^{-1} at age 3 yr	$T_{1333/3}$	No fertiliser	F_0	0.60
	Thinned to 1000 trees ha^{-1} at age 3 yr	$T_{1000/3}$	No fertiliser	F_0	0.60
	Thinned to 667 trees ha^{-1} at age 3 yr	$T_{667/3}$	No fertiliser	F_0	0.60
Dong Nai (4.9 yr)	No thinning (1111 trees ha^{-1})	NT_{1111}	No fertiliser	F_0	0.70
	Thinned to 600 trees ha^{-1} at age 2 yr	$T_{600/2}$	No fertiliser	F_0	0.70
	Thinned to 600 trees ha^{-1} at age 3 yr	$T_{600/3}$	No fertiliser	F_0	0.70
	Thinned to 800 trees ha^{-1} at age 2 yr, then thinned to 600 trees ha^{-1} at age 3 yr	$T_{800/2}T_{600/3}$	No fertiliser	F_0	0.70

[a]Basal fertiliser included: 80 KCl kg ha^{-1}, 6 $MnSO_4.H_2O$ kg ha^{-1}, 64 $FeSO_4.7H_2O$ kg ha^{-1}, 3.5 $ZnSO_4.7H_2O$ kg ha^{-1}, 2 $CuSO_4.xH_2O$ kg ha^{-1}, 0.45 H_3BO_3 kg ha^{-1}, 0.11 $Na_2MoO_4.2H_2O$ kg ha^{-1}, 12 $MgSO_4$ kg ha^{-1}.

4.2.3. Stand growth and yield

Total tree height (*H*, m) and diameter at breast height (*DBH*, cm) of all individual trees and stem number (*N*, trees ha^{-1}) in each sample plot were measured at six-monthly intervals from 2009 to 2015. These measurements were used to calculate plot mean *DBH* and stand volume (*SV*, m^3 ha^{-1}). The individual tree volume (*V*, m^3 $tree^{-1}$) was calculated as:

$$V = \frac{\pi}{4} \times DBH^2 \times H \times f \tag{4.1}$$

Where *f* is a stem form factor (*f* = 0.495) (Binh, 2003). Stand volume was then calculated as the sum of *V* of all individual trees in each plot and expressed on a per hectare basis.

Diameter classes were divided into four groups according to wood products: *DBH* <10 cm (pulp wood), 10 cm ⩽ *DBH* <13.9 cm and 14 cm ⩽ *DBH* <17.9 cm (small sawlogs, SSL) and *DBH* ⩾18 cm (larger sawlogs, LSL).

4.2.4. Application of 3-PG model

3-PG is a process-based model of forest productivity that uses a simple concept of conversion of photosynthetically active radiation absorbed by the canopy through the photosynthesis process to net primary production (Landsberg and Sands, 2010). The model has been described in detail by Landsberg and Sands (2010) and applied widely for different purposes for several species growing under current and future climate

(Sands and Landsberg, 2002; Almeida et al., 2004a; Almeida et al., 2007; Almeida et al., 2009; González-García et al., 2016) . 3-PG has been recently modified by Almeida and Sands (2016) incorporating a more detailed water balance sub-model. The model is capable of producing a range of outputs of interest to the forest manager (Almeida et al., 2004b; Sands, 2004) but for this study, the model was used to examine the effects of thinning and fertiliser treatments on the product yield of small (SSL, *DBH* 14-17.9 cm) and large sawlog (LSL, *DBH* ⩾18 cm) production for a rotation length up to 15 yr.

The model soil fertility empirical index (*FR*) ranges from one (no nutritional limitations) to zero (extremely infertile). For the different sites in this study, *FR* values for *A.* hybrid had been determined by a previous study (Hung et al. 2016) and ranged from 0.3 to 0.8. For the plots that received fertiliser at thinning (i.e. F1 and F2), it was assumed that the application of fertiliser increased the initial *FR* by 10% - a value obtained from empirical evidence for *Eucalyptus grandis* × *urophylla* (Stape et al., 2004) (Table 2). For the thinned plots that received no fertiliser at thinning (F0), the *FR* values were the same values of control plots.

Monthly modelled *DBH* and *SV* of each treatment from 1 to 15 years were used to identify the time predicted for each treatment to reach the required mean *DBH* for both SSL and LSL, defined as minimum harvest ages for each log type. The measured *DBH* and *SV* responses to thinning and fertiliser at thinning were also used to identify the most successful management practice to produce sawlogs of a given size at harvest.

4.2.5. Statistical analysis

As the treatments and timing of measurements were different, each site was analysed separately. Survival rate (82.1 – 96%) was similar regardless of thinning and fertiliser treatments from tree age 4.9 to 5.7 years (data not shown). Effects of thinning and fertiliser treatments on *DBH* and *SV* were analysed by two-way analysis of variance (ANOVA) within a repeated measure framework assuming a randomised block design with fertiliser and thinning treatments as fixed factors. Effects of thinning and fertiliser treatments on diameter classes, 10-13.9 and 14-17.9 cm at final measurement, were analysed by two-way ANOVA. Due to lack of data, diameter classes, <10 and >18 cm were not analysed. The assumptions of ANOVA such as homogeneity of variance and the Gaussian distribution were checked by the use of quantile–quantile plots and residual plots for all variables. Fisher's protected least significant difference (LSD at P <0.05) post-hoc tests were used to determine differences among treatment means. All analyses were performed using GenStat, 12th edition (VSN International Ltd, Hemel Hempstead, UK 2011).

The fit between predicted and observed *DBH* and *SV* values were assessed by calculating the coefficient of determination (r^2), model efficiency (*EF*) (Loague and Green, 1991) and the root mean square error (*RMSE*) (Soares et al., 1995) as follows:

$$EF = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{4.2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - \bar{O})^2}{n}} \tag{4.3}$$

Where *Pi* and *Oi* are the predicted and measured values respectively, $\bar{O}$ is the mean of the observed values, and *n* is the total number of measurements.

4.3. Results

4.3.1. Effects of thinning regimes on *DBH* and *SV*

Significant responses of *DBH* and *SV* to thinning intensity occurred at Tuyen Quang, Ba Vi-1, Ba Vi-2 and Ba Vi-3, but there were no significant differences in *SV* between T_{450} and T_{600} at Ba Vi-3. At Binh Dinh and Dong Nai, thinning intensity did not affect *DBH*, but *SV* in thinned treatments was significantly lower than in the unthinned treatment (Appendix Figures 4.2 and 4.3).

4.3.2. Effects of thinning intensity × tree age interaction on *DBH* and *SV*

Tree age is the age at which the tree was measured after planting. Both *DBH* and *SV* were significantly influenced by thinning intensity × tree age interaction across all trials (Appendix Figures 4.2 and 4.3).

At Tuyen Quang and Ba Vi-1, *DBH* was significantly greater compared to unthinned treatments five months after thinning ($T_{600/2}$) (Figure. 4.1a, b). These differences remained significant at final measurement. In contrast, thinning treatments had no significant immediate effect on *DBH* when thinning was carried out at age ⩾3 years at Ba Vi-2, Binh Dinh and Dong Nai, (Figure 4.1c-e). Instead, significant thinning effects were observed later, at age 4.4 – 7.4 years, with the magnitude and timing of these differences to thinning intensity varying across trials (Figure 4.1). Similarly, at

Binh Dinh, the effect of thinning treatment was observed later, at tree age 5.3 years when *DBH* (13.3 cm) was the highest in $T_{667/3}$ compared to $T_{1000/3}$ and $T_{1333/3}$ (12.6 and 12.2 cm, respectively), and NT_{2000} (12.0 cm) (Figure 4.1d). At Dong Nai, significant responses of *DBH* to all thinning treatments were first observed at tree age 4.4 years with *DBH* of $T_{600/2}$, $T_{600/3}$ and $T_{800/2}T_{600/3}$ being significantly larger than NT_{1111}. However, this response was not sustained for $T_{600/3}$ at tree age 4.9 years and there were no significant differences in *DBH* between $T_{600/2}$ and $T_{800/2}T_{600/3}$ (Figure 4.1e).

Across all trials, thinning treatments significantly reduced *SV* immediately after the thinning event (Appendix Table 4.1 and Figure 4.4). For example, *SV* of $T_{600/2}$ in Tuyen Quang, Ba Vi-1 and Ba Vi-2 and $T_{600/3.5}$ in Ba Vi-2 were significantly lower compared to unthinned treatments and this significant treatment effect was sustained until the final measurement (Appendix Figure 4.2a-c). At Binh Dinh, by tree age 5.4 year, *SV* of $T_{1000/3}$ and $T_{1333/3}$ treatments were similar but both were significantly higher than $T_{667/3}$ and lower than NT_{2000} (Appendix Figure 4.2d). At Dong Nai, by tree age 3.7 years, *SV* of $T_{600/2}$, $T_{600/3}$ and $T_{800/2}T_{600/3}$ was similar and all significantly lower than those of NT_{1111}. These differences remained significant at final measurement (Appendix Figure 4.2e).

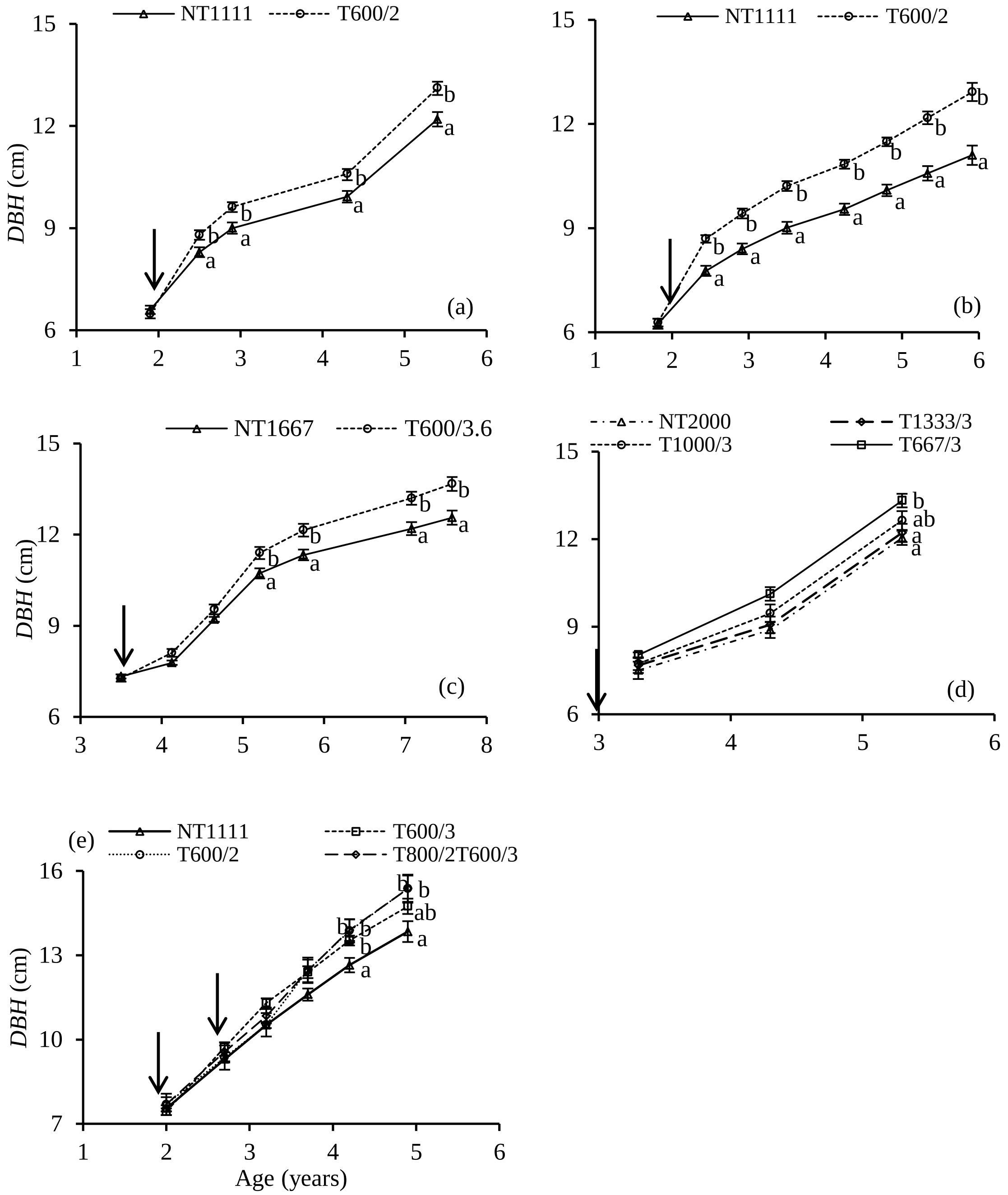


Figure 4.1 Thinning intensity × tree age interaction on DBH (cm) at Tuyen Quang (a), Ba Vi-1 (b), Ba Vi-2 (c), Binh Dinh (d) and Dong Nai (e). Different letters indicate that means are significantly different at P <0.05 within a measurement period. Arrows indicate the timing of thinning. See Table 4.2 for codes and description of treatments.

4.3.3. Effects of thinning intensity × timing of thinning × tree age interaction on *DBH* and *SV*

The effects of thinning intensity (NT_{1667}, T_{450}, T_{600} and T_{900}) and timing of thinning (3.6, 4.6 and 5.6 years) on *DBH* and *SV* varied across treatments at Ba Vi-3 (Figure 4.3). When measured at age 7.4 years, the *DBH* of all thinned treatments were greater than those of unthinned treatments, but the *SV* was lower compared to unthinned treatments (Figure 4.3 and Appendix Figure 4.3).

When trees were thinned at tree age 3.6 years, the effect of thinning treatments was first observed seven months after thinning (Figure 4.3a). In particular, *DBH* was significantly higher as thinning intensity increased and this response was sustained until tree age 7.6 years ($T_{450} > T_{600} > T_{900}$). In contrast, for trees thinned at tree age 4.6 and 5.6 years, significant thinning responses were observed 13 and 15 months later, respectively (Figure 4.3b, c). Specifically, the *DBH* of all thinned treatments were similar, regardless of thinning intensity though they were all significantly higher than the unthinned treatment (Figure 4.3b, c).

The *SV* of all the thinned treatments was significantly lower compared to unthinned treatments immediately after the thinning event (Appendix Figure 4.3). For trees thinned at tree age 3.6 years, these differences remained significant until the final measurement (Appendix Figure 4.3a). However, when trees were thinned at tree age 4.6 and 5.6 years, *SV* between T_{450} and T_{600} were similar, though both treatments were significantly lower than either T_{900} or NT_{1667} (Appendix Figure 4.3b and c).

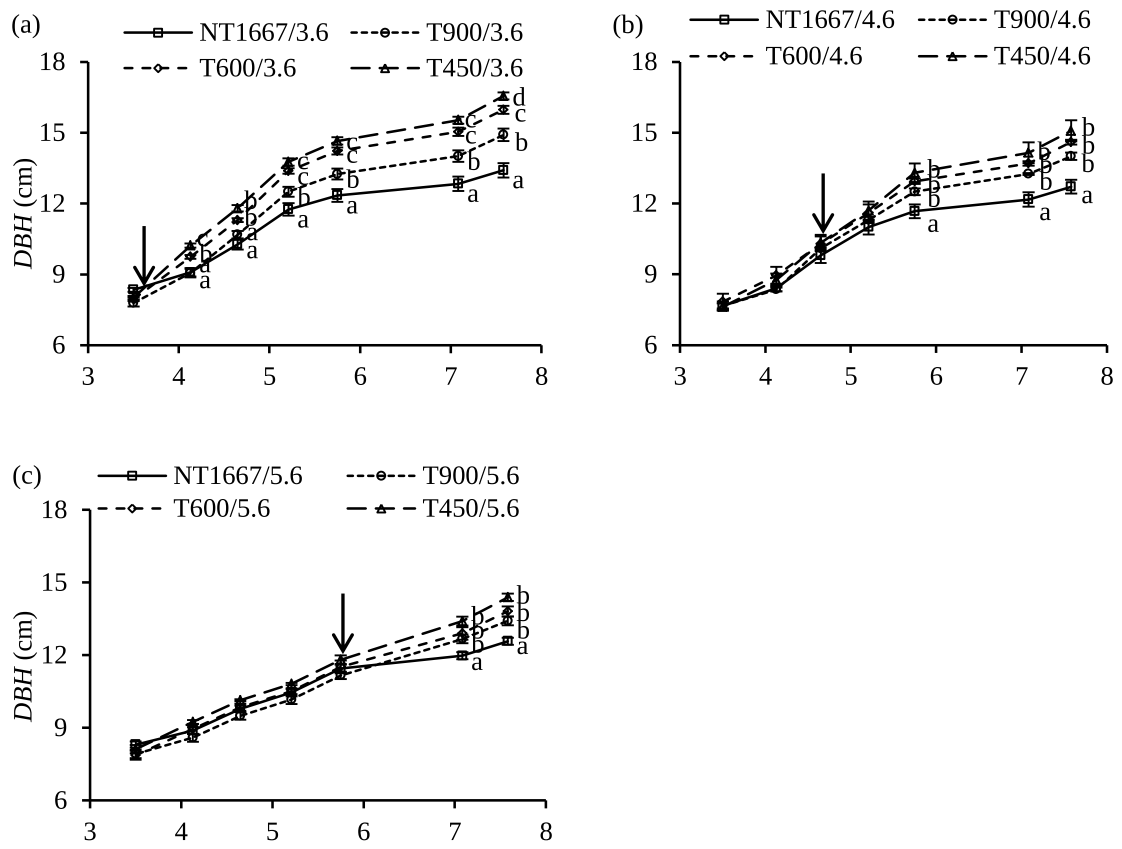


Figure 4.2 Thinning intensity × timing of thinning interaction on DBH (cm) for three sites at Ba Vi-3. Different letters indicate that means are significantly different at $P < 0.05$ within a measurement period. Arrows indicate the timing of thinning. See Table 4.2 for codes and description of treatments.

4.3.4. Effects of fertiliser application at thinning × tree age on *DBH* and *SV*

Significant responses of *DBH* to the F_2 treatment at thinning were observed four or five months after fertiliser application at Tuyen Quang and Ba Vi-1 (Appendix Table 4.1, Figure 4.3a, b); the response was observed at a later stage (1.7 years) after fertiliser application at Ba Vi-2 (Appendix Table 4.1, Figure 4.3c). At Tuyen Quang, fertiliser had a significant effect on *DBH* at the final measurement however, the magnitude of this response did not vary between F_1 and F_2 treatments (Figure 4.3a). At Ba Vi-1 and

Ba Vi-2, *DBH* of the F_2 treatment was significantly greater than those in the F_1 and F_0 treatments at 5.4 and 7.1 years, respectively (Figure 4.3b, c).

At Tuyen Quang, fertiliser treatment had no effect on *SV* (Appendix Figure 4.4a). In contrast, at Ba-Vi-1 and Ba Vi-2, the *SV* of the F_2 treatment was significantly greater compared to both the F_1 and F_0 treatments, 0.6 and 1.7 years, respectively after fertilising and these differences were maintained until the final measurement (Appendix Figure 4.4b, c).

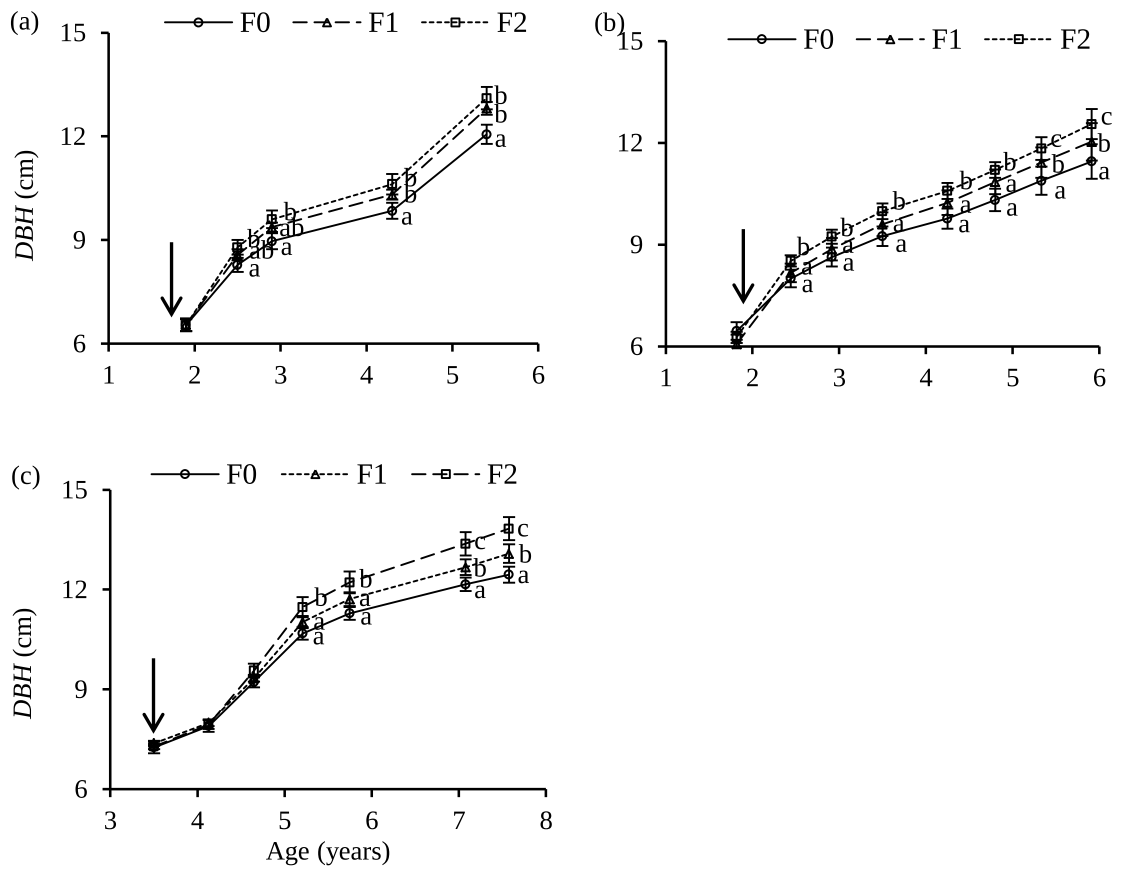


Figure 4.3 Effect of fertiliser-at-thinning application × tree age interaction on DBH (cm) at Tuyen Quang (a), Ba Vi-1 (b) and Ba Vi-2 (c). Different letters indicate that means are significantly different at P <0.05 within a measurement period. Arrows indicate the timing of fertiliser application. See Table 4.2 for codes and description of treatments.

4.3.5. Effects of silvicultural treatments on *DBH* classes

At Tuyen Quang, Ba Vi-1, Ba Vi-2 and Ba Vi-3, thinned treatments had significantly higher percentage of trees in the 14 – 17.9 cm than the 10 – 13.9 cm class compared to the unthinned treatment (Table 4.3 and Appendix Table 4.3). However, at Ba-Vi 3, the percentage of trees in the 10 – 13.9 cm and 14 – 17.9 cm *DBH* classes for the T_{450} treatment were significantly higher than T_{900} and T_{600} treatments. At Binh Dinh, thinning treatment had no significant influence on *DBH* classes (Table 4.3). At Dong Nai, only the 10 – 13.9 cm class was affected by thinning treatment. In particular, $T_{800/2}T_{600/3}$ had 62% less trees with this class than NT_{1111} treatment. The percentage of trees in the 14 – 17.9 cm class in all thinned treatment showed greater values compared to NT_{1111} treatment (P = 0.062) (Table 4.3).

At Ba Vi-1, diameter classes were unaffected by fertiliser (Appendix Figure 4.6). In contrast, a significantly higher percentage of trees in the 14 – 17.9 cm class was observed in the F_1 and F_2 treatments than the F_0 treatment at Ba Vi-2; there were no significant differences between F_1 and F_2 treatments (Table 4.4). At Tuyen Quang, only the F_2 treatment significantly increased trees in the 14 – 17.9 cm class (Table 4.4).

Thinning intensity × fertiliser interaction had a significant effect on diameter classes at both Tuyen Quang and Ba Vi-1 only (Table 4.5). At Tuyen Quang, the percentage of trees in the 14 – 17.9 cm class was highest under $T_{600/2}F_2$ followed by $T_{600/2}F_1$. The percentage of trees in this class was similar in NT_{1111} at Tuyen Quang, regardless of fertiliser treatment. At Ba Vi-1, fertiliser had no effect on the percentages of trees in the 10 – 13.9 cm class under $T_{600/2}$. In contrast, significantly higher percentages of trees were observed in the F_2 but not in the F_1 nor F_0 treatments in NT_{1111}.

At Ba Vi-3, timing of thinning significantly influenced the percentage of trees in the 10 – 13.9 cm but not the 14 – 17.9 cm class (Appendix Table 4.3); a significantly lower percentage of trees in the 10- 13.9 cm class were observed for trees thinned at age 3.6 than those thinned at age 4.6 and 5.6 (i.e. thinning age 3.6: 23.6 ± 6.2%; thinning age 4.6: 32.2 ± 6.2%; thinning age 5.6: 38.7 ±6.6%).

Table 4.3 Effect of thinning intensity on distribution of stem diameter classes (%) at final measurement age of six experimental trials in Vietnam. Different letters indicate that treatment means are significantly different at *P* <0.05 within a diameter class.

Trial (final tree age)	<10 cm	10 – 13.9 cm	14 – 17.9 cm	⩾18 cm
Tuyen Quang (5.4 yr)				
NT_{1111}	0	46.0b	54.0a	0
$T_{600/2}$	0.9	26.0a	73.1b	0
Ba Vi-1 (5.9 yr)				
NT_{1111}	35.1	64.2a	0.7a	0
$T_{600/2}$	1.2	89.8b	9.0b	0
Ba Vi-2 (7.4 yr)				0
NT_{1667}	5.3	76.1b	18.6a	0
$T_{600/3.6}$	0.4	50.6a	49.0b	0
Ba Vi-3 (7.4 yr)				
NT_{1667}	1.4	70.2c	28.3a	0.1
T_{900}	0	29.7b	70.0b	0.3
T_{600}	0	21.9b	76.0b	2.1
T_{450}	0	4.2a	88.1c	7.7
Binh Dinh (5.3 yr)				
NT_{2000}	11.0	72.5	16.5	0
$T_{1333/3}$	7.8	77.7	14.5	0
$T_{1000/3}$	1.0	84.9	14.1	0
$T_{667/3}$	0	72.8	27.2	0
Dong Nai (4.9 yr)				
NT_{1111}	9.3	41.5b	44.4	4.8
$T_{600/2}$	1.7	27.3ab	62.5	8.5
$T_{600/3}$	1.7	30.4ab	59.4	8.5
$T_{800/2}T_{600/3}$	1.8	15.7a	73.9	8.6

Table 4.4 Effect of fertiliser treatment on distribution of stem diameter classes (%) at the final measurement age of three experimental trials at Tuyen Quang, Ba Vi-1 and Ba Vi-2. Different letters indicate that treatment means are significantly different at *P* <0.05 within a diameter class.

Trial (tree age)	<10 cm	10 – 13.9 cm	14 – 17.9 cm
Tuyen Quang (5.4 yr)			
F_0	4.9	84.8a	9.4a
F_1	0	84.4a	15.6a
F_2	0.5	85.7b	27.0b
Ba Vi-1 (5.9 yr)			
F_0	4.6	74.4	1.8
F_1	2.0	72.3	5.7
F_2	1.0	84.2	7.2
Ba Vi-2 (7.4 yr)			
F_0	3.9	76.3b	19.8a
F_1	4.3	61.6ab	34.1b
F_2	0.3	52.1a	47.6b

Table 4.5 Effect of thinning intensity × fertiliser interaction on distribution of stem diameter classes (%) at the final measurement age at Tuyen Quang and Ba Vi-1. Different letters indicate that means are significantly different at *P* <0.05 within a diameter class.

Trial (tree age)	<10 cm	10 – 13.9 cm	14 – 17.9 cm
Tuyen Quang (5.4 yr)			
$NT_{1111}F_0$	7.1	87.2b	5.7a
$T_{600/2}F_0$	2.6	84.2b	13.2ab
$NT_{1111}F_1$	0	89.9b	10.1ab
$T_{600/2}F_1$	0	78.9b	21.1b
$NT_{1111}F_2$	1.1	88.8b	10.1ab
$T_{600/2}F_2$	0	56.1a	43.9c
Ba Vi-1 (5.9 yr)			
$NT_{1111}F_0$	46.0	54.0a	0
$T_{600/2}F_0$	1.8	94.7b	3.5
$NT_{1111}F_1$	42.2	57.8a	0
$T_{600/2}F_1$	1.9	86.8b	11.3
$NT_{1111}F_2$	17.2	80.8b	2.0
$T_{600/2}F_2$	0	87.7b	12.3

4.3.6. Modelling growth and sawlogs yields

The 3-PG model predicted *DBH* and *SV* for all treatments though the accuracy of the predictions varied with treatments across trials. The *EFs* of *SV* ranged from 0.55 to 0.98 (*RMSEs* = 1.88 – 27.71) while the *EFs* of *DBH* ranged from 0.53 to 0.96 (*RMSEs* = 0.97 – 2.48) (Fig. 4 and Table A4).

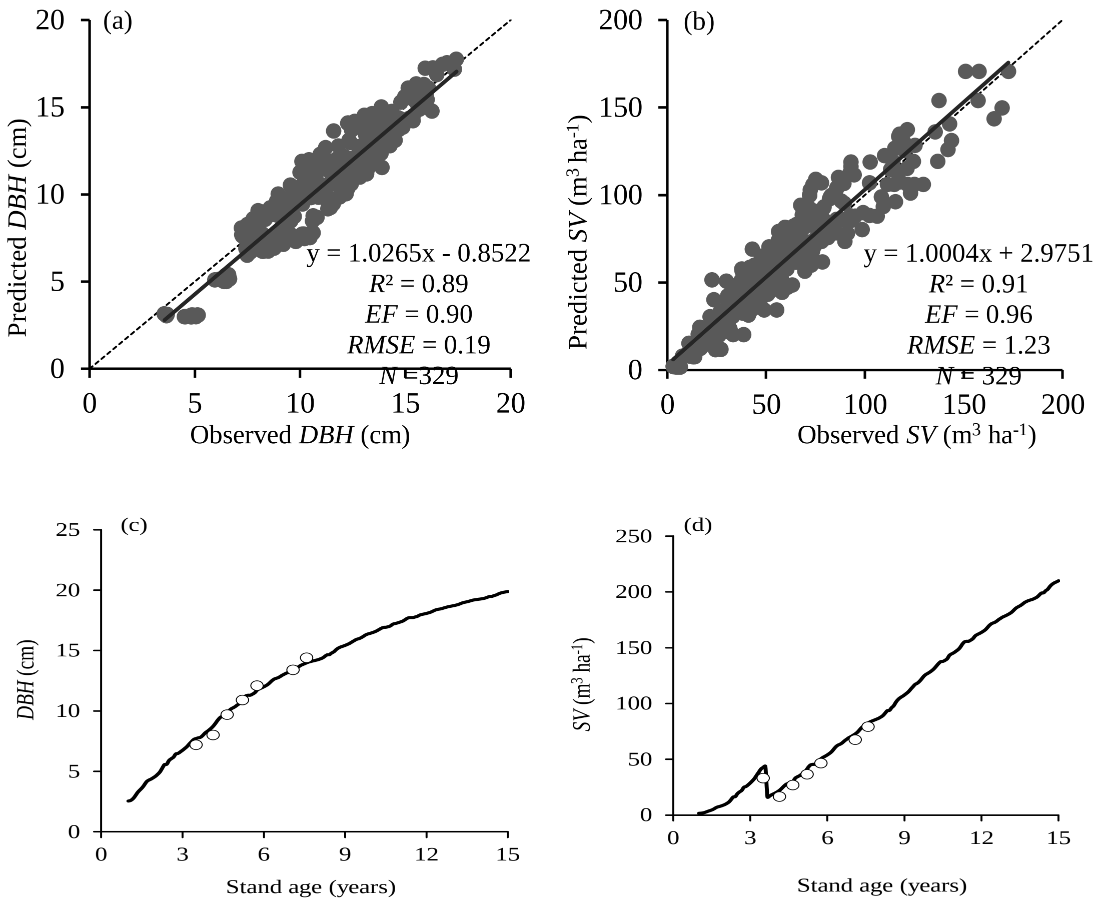


Figure 4.4 Relationships between observed and predicted (a) *DBH* (cm) and (b) *SV* (m^3 ha^{-1}) as determined by 3-PG for all thinning and fertiliser treatments across six the experimental trials. Predicted (---) and observed (o) time series of (c) *DBH* (cm) and (d) *SV* (m^3 ha^{-1}) for Ba-Vi 2 site thinned from 1667 to 600 trees ha^{-1} at age 3.6 years. Dots represent means of 35 – 42 trees plot^{-1}.

Model predictions of *DBH* showed that, in unthinned treatments, the rotation length required to obtain small sawlogs (14 – 17.9 cm *DBH*) was approximately half that required for larger sawlogs (⩾18 cm *DBH*) (Table 4.6). At the end of the simulation, predicted *SV* in thinned treatments was 5 – 20% less than *SV* in unthinned treatments across trials for a 15-year rotation.

Model predictions of the minimum rotation length to produce small logs ranged between 4.8 – 8.3 years for all thinned treatments compared to 6.2 – 12.8 for all unthinned treatments (Table 4.6). For large logs, the minimum predicted rotation length ranged between 7.3 – 12.7 years in all thinned treatments compared to 10.4 – >15 years in all unthinned treatments.

At Tuyen Quang, Ba Vi-1, Ba Vi-2 and Ba Vi-3, no large sawlogs were predicted for any unthinned treatment at the end of a 15-yr rotation. In contrast, at Bing Dinh and Dong Nai, all thinning intensities including the unthinned treatment were predicted to produce both small and larger sawlogs within a 15-yr rotation.

At Ba Vi-3, the simulations indicated that the rotation length required to grow the trees to either small or large diameter would be shorter by 0.5 to 1.7 years if thinning was carried at age 3.6 years compare to ages 4.6 or 5.6 years. Heavy early age thinning also predicted less time would be required to produce sawlog products compared to lighter early age thinning. At Tuyen Quang, Ba Vi-1 and Ba Vi-2, simulations with fertiliser application at thinning predicted rotation lengths for small sawlogs were between 0.5 to 2.6 years shorter compared with thinning only and fertiliser control treatments.

Table 4.6 3-PG modelling of product yield of small (*DBH* ⩾14 cm) and large sawlog (*DBH* ⩾18 cm) at minimum harvest age (Min. age, year) for a 15-yr rotation for all thinning and fertiliser treatments for each experimental trial.

Trial/treatment	Min. age to reach *DBH* ⩾14 cm (year)	Min. age to reach *DBH* ⩾18 cm (year)	*SV* at min. age *DBH* ⩾14 cm (m^3 ha^{-1})	*SV* at the min age *DBH* ⩾18 cm (m^3 ha^{-1})	*DBH* at age 15 yr (cm)	*SV* at age 15 yr (m^3 ha^{-1})
Tuyen Quang						
$NT_{1111}F_0$	9.8	>15	157.1	N/A	16.6	243.3
$T_{600/2}F_0$	6.3	11.2	83.1	162.9	20.1	215.4
$NT_{1111}F_1$	7.2	>15	117.5	N/A	17.4	273.6
$T_{600/2}F_1$	5.8	9.8	81.5	163.4	21.2	247.4
$NT_{1111}F_2$	8.6	>15	154.7	N/A	17.5	279.5
$T_{600/2}F_2$	5.6	9.6	80.9	161.5	21.4	253.7
Ba Vi-1						
$NT_{1111}F_0$	9.2	>15	155.1	N/A	17.1	261.3
$T_{600/2}F_0$	5.8	10.1	81.4	162.3	20.9	238.6
$NT_{1111}F_1$	8.5	>15	155.6	N/A	17.9	293.1
$T_{600/2}F_1$	5.3	9.3	79.3	162.9	21.9	269.9
$NT_{1111}F_2$	8.3	>15	155.1	N/A	18.0	299.2
$T_{600/2}F_2$	5.3	9.1	80.8	161.6	22.1	275.9
Ba Vi-2						
$NT_{1667}F_0$	12.8	>15	234.5	N/A	14.8	271.5
$T_{600/3.6}F_0$	8.0	12.3	83.6	162.7	19.6	202.8
$NT_{1667}F_1$	11.4	>15	233.5	0.0	15.5	302.7
$T_{600/3.6}F_1$	7.5	10.8	92.1	163.2	20.9	237.9
$NT_{1667}F_2$	11.3	>15	234.5	0.0	15.6	308.7
$T_{600/3.6}F_2$	7.0	10.7	83.1	162.2	21.1	244.0
Ba Vi-3						
$NT_{1667/3.6}F_0$	9.9	>15	233.6	N/A	16.6	361.0
$T_{900/3.6}F_0$	7.2	11.7	126.4	243.0	20.0	321.0
$T_{600/3.6}F_0$	6.2	9.3	82.2	164.0	22.7	297.9
$T_{450/3.6}F_0$	5.7	8.3	60.1	121.2	24.7	277.8
$NT_{1667/4.6}F_0$	9.9	>15	233.6	N/A	16.6	361.0
$T_{900/4.6}F_0$	7.7	12.3	124.1	245.8	19.7	308.3
$T_{600/4.6}F_0$	6.9	10.1	82.8	162.8	22.1	277.0
$T_{450/4.6}F_0$	6.7	9.3	62.8	121.0	23.7	250.6
$NT_{1667/5.6}F_0$	9.9	>15	233.6	N/A	16.6	361.0
$T_{900/5.6}F_0$	8.3	12.7	126.3	243.8	19.4	296.0
$T_{600/5.6}F_0$	7.7	10.8	84.0	162.4	21.5	257.9
$T_{450/5.6}F_0$	7.4	10.0	62.7	121.9	23.0	230.5
Binh Dinh						
$NT_{2000}F_0$	7.4	12.3	233.3	410.7	21.8	481.9
$T_{1333/3}F_0$	7.7	12.7	231.3	410.7	20.8	462.9
$T_{1000/3}F_0$	6.2	9.6	135.4	272.0	22.0	458.4
$T_{667/3}F_0$	5.3	7.6	88.6	181.8	25.5	445.8
Dong Nai						
$NT_{1111}F_0$	6.2	10.4	154.0	301.4	20.8	438.8
$T_{600/2}F_0$	4.9	7.3	78.4	161.9	25.3	393.9
$T_{600/3}F_0$	5.1	7.7	82.0	160.4	24.5	362.6
$T_{800/2}T_{600/3}F_0$	4.8	7.3	79.2	162.7	24.8	373.0

N/A = not applicable

4.4. Discussion

4.4.1. Growth responses to thinning

Thinning to 450 and 600 trees ha^{-1} at age 2 – 3 years produced the highest percentage of larger *DBH* classes although there was lower *SV* in all thinned stands especially those thinned to 450 trees ha^{-1}. Thinning to 900 and 1000 trees ha^{-1} may sustain high growth rates in stands with initial stocking of ⩾1667 trees ha^{-1}.

Increased *DBH* increment of retained trees due to early thinning has been reported in other studies on hardwood species especially *Eucalyptus* (Medhurst et al., 2001; Forrester et al., 2012). The *DBH* growth response to thinning indicates that intraspecific competition prior to thinning occurred as early as 2 years. Early thinning especially at higher intensities may reduce this intraspecific competition to allow increased leaf area index (West, 2014) and potentially improve efficiency in nutrient and water use (Aussenac and Granier, 1988; Medhurst et al., 2002).

Significant responses to later age thinning found in this study have also been reported in previous studies for other tree species e.g. *A. mangium* (Kamo et al., 2009) and *E. nitens* (Medhurst and Beadle, 2001; Forrester et al., 2013b).

A compromise is sought between the optimum tree volume for sawlog and the time of thinning to maximise the recovery of pulpwood (Forrester et al., 2013b). In Vietnam where *A.* hybrid plantations are mainly grown by smallholders requiring a quick return on investment and consequently aiming to reduce the rotation length. Our results showed the advantage of early thinning (before 3.6 years) at an intensity of 450 or 600 trees ha^{-1} to maximise the percentage recovery of small and large sawlogs within the shortest rotation. Depending on site productivity and the location of the nearest mill, the thinned trees may be an appropriate size for selling to the pulp mill (Beadle, personal communication).

4.4.2. Growth responses to fertiliser

Fertiliser application increased the thinning responses resulting in significantly greater *DBH* which was sustained until the final measurement. Similar responses to thinning and fertiliser treatments were found in *E. nitens* plantations (Forrester et al., 2012).

The response to fertiliser found in the experimental sites is probably driven by low P levels in the soil. Lateritic low pH (3.4 – 4.4) soils strongly fix P and available P is only 1.8 – 4.9 mg kg^{-1}. Xu and Dell (2002) found that low pH and available P in soils are key factors that often result in an increase of eucalypt growth in response to P fertiliser application in China. In this study, a significant growth response to fertiliser was observed in at Ba Vi-2, where slash and litter had been removed. These results suggest that retaining litter may be an important management strategy for reducing fertiliser inputs

Less nutrient limiting sites may not require P fertiliser at thinning and the total amount of P fertiliser per tree applied at planting may be sufficient to obtain thinning response (Huong et al., 2016). Nutritional requirements however, may change over successive rotations, depending on soil type, growth rates, and inter-rotation management practices (Nambiar and Harwood, 2014).

4.4.3. Modelling the effects of thinning and fertilisation on stand growth

The 3-PG model has been used to simulate response to thinning (Landsberg et al., 2005; Pérez-Cruzado et al., 2011; Rodríguez et al., 2015) and fertilization (Stape et al., 2004; Wei et al., 2014). This study showed that 3-PG was able to predict stand growth, with acceptable accuracy at least for the period when measurements were made i.e. up to 7.4 years after planting. The model was more accurate in predicting *DBH* and *SV* for treatments in north (Tuyen Quang, Ba Vi-1, Ba Vi-2, Ba Vi-3) and south central coast Vietnam (Bing Dinh) than the more highly productive site in south Vietnam (Dong Nai). This observed variation in model accuracies between regions and sites could potentially be due to the fact that calibration of the model was based on a single parameter set developed for one site (Ba Vi) for a limited number of clones (four out of the seven clones only); accuracy of climatic data between sites and distance from the weather stations and the uncertainties of the effect of fertilisation on the FR values. In general, the model accuracy observed in this study was similar to those reported for other species such as *Eucalyptus grandis* (Almeida et al., 2004a), *Eucalyptus nitens* (González-García et al., 2016) and in more complex scenarios such as mixed species plantations (Forrester and Tang, 2016). However, this is the first time the 3-PG model has been applied to predict multi products and thinning treatments for *A. hybrid* plantations.

In this study, the mean annual increment (*MAI*) observed and modelled for *A. hybrid* ranged from 15 to 33 m^3 ha^{-1} $year^{-1}$ with Dong Nai and Binh Dinh being (25 and 30 m^3 ha^{-1} $year^{-1}$, respectively) higher than Ba Vi and Tuyen Quang (14 to 23 m^3 ha^{-1} $year^{-1}$). These values are similar to those reported for *A. hybrid* in Central Vietnam (e.g. > 25 m^3 ha^{-1} $year^{-1}$, Beadle et al. 2013a) and for *Acacia mangium* in Sumatra, Indonesia (22 to 35 m^3 ha^{-1} $year^{-1}$, Harwood and Nambiar, 2014).

Modelling a 15-year rotation length enabled the prediction of the volume of pulpwood, small sawlog and large sawlog production for different ages. As for the time series measurements, simulations suggest that heavy early age thinning associated with fertiliser application will produce larger log sizes in shorter time, compared to low intensity and later-age thinning. Simulations indicate that a proportion of small (*DBH* ⩾14 cm) and larger (*DBH* ⩾18 cm) sawlogs can be obtained in north Vietnam within rotation lengths of 6 and 10 years, respectively. The rotation lengths projected in south and south central coast Vietnam were 5 years for small sawlogs and 7 years for larger sawlogs. It is acknowledged that these estimations are based on a model that has been validated for stands up to age 7.4 years and beyond this age, more data need to be collected to corroborate the modelling results. However, these results indicate potential variability in terms of silvicultural treatments and optimum rotation lengths across Vietnam that may influence the decision making process to obtain saw logs in shorter rotations.

4.5. Conclusions

Earlier- and later-age thinning to 450 or 600 trees ha^{-1} increased sawlog proportion of larger diameter logs within 5 to 10 years. Less intense thinning to 900 or 1000 trees ha^{-1} also produced small sawlog but with lower proportion of the total volume. Fertiliser application increased tree growth, especially at a thinning density of 600 trees ha^{-1}. The range of responses observed in this study provide information of potential management across a range of thinning prescriptions and site qualities; the decision of what management is suitable for a particular region depends on the markets for thinned products.

The 3-PG model adequately predicted the growth of *A.* hybrid plantations under thinning and fertilisation regimes, up to 7.4 years after planting. The model predictions suggested that the rotation of thinned stands with 5 – 7 years in south and central, and 6 – 10 years in north produces small and large saw logs. The results from both the empirical and modelling studies provide smallholders with information to assist with decision making of stands over the entire rotation period to achieve production of the required diameter sizes in the shortest time possible and to optimise sustainable management of *A.* hybrid plantations in Vietnam.

Variability between species, sites, costs of inputs and the value of products shows that there is no single optimal fertilising and thinning regime. Further recommendations to undertake thinning or fertiliser operations should include an examination of the potential effect of thinning wood properties (e.g. wood density, stem taper) as well as socio-economic analyses that considers timber prices, costs of management practices, the applied discount rate, transport costs and the cash flow requirements of smallholders. Thus, the final assessment of the feasibility of intensive management can only be performed after a financial analysis that needs to consider the risks associated with longer rotations, which remains a task of further study.

Appendices

Appendix Table 4.1 Summary of repeated measures analysis of variance showing the effects of thinning rate, thinning time, fertiliser, time, and their interactions on *DBH* and *SV* of the six experimental trials in Vietnam. **P* <0.05; ***P* <0.01; ****P* <0.001; ns, not significant.

Trial	Effect	DF	*P* value	
			DBH	*SV*
Tuyen Quang	Thinning intensity (T)	1	**	***
	Fertiliser (F)	2	*	ns
	Tree age (A)	6	***	***
	T × F	2	ns	ns
	F × A	12	***	ns
	T × A	6	***	***
	T × F × A	12	ns	ns
Ba Vi-1	T	1	***	***
	F	2	**	**
	A	6	***	***
	T × F	2	ns	ns
	F × A	12	***	***
	T × A	6	***	***
	T × F × A	12	ns	ns
Ba Vi-2	T	1	***	***
	F	2	**	**
	A	8	***	***
	T × F	2	ns	ns
	F × A	16	***	***
	T × A	8	***	***
	T × F × A	6	ns	ns
Ba Vi-3	T	3	***	***
	Timing of thinning (t)	2	***	***
	A	6	***	***
	T × t	6	**	**
	T × A	18	***	***
	t × A	12	***	***
	T × t × A	36	***	***
Binh Dinh	T	3	ns	***
	A	2	***	***
	T × A	6	***	***
Dong Nai	T	3	ns	*
	A	2	***	***
	T × A	18	***	***

Appendix Table 4.2 Effects of a) thinning intensity and b) fertiliser on *DBH* and *SV* at the six experimental trials. Different letters indicate that means are significantly different at $P < 0.05$ within a diameter class.

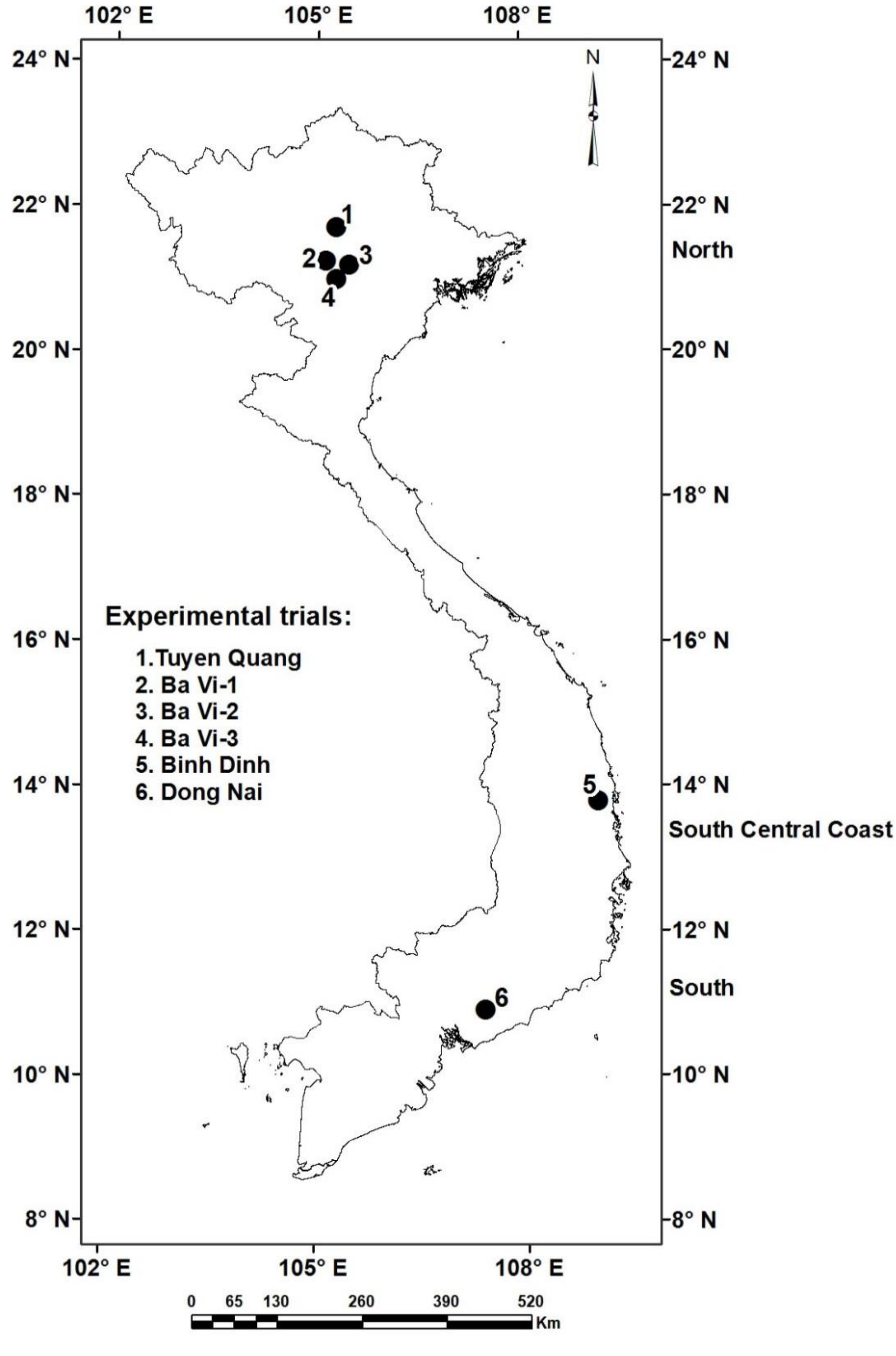
Trial (tree age)	*DBH* (cm)	*SV* (m^3 ha^{-1})
a) Thinning intensity		
Tuyen Quang (5.4 yr)		
NT_{1111}	7.6a	24.1b
$T_{600/2}$	8.0b	16.9a
Ba Vi-1 (5.9 yr)		
NT_{1111}	7.7a	32.3b
$T_{600/2}$	8.7b	23.5a
Ba Vi-2 (7.4 yr)		
NT_{1667}	10.1a	82.4b
$T_{600/3.6}$	10.7b	38.9a
Ba Vi-3 (7.4 yr)		
NT_{1667}	11.0a	92.8a
T_{900}	11.6b	80.5b
T_{600}	11.9c	76.7bc
T_{450}	12.3d	70.7bc
Binh Dinh (5.3 yr)		
NT_{2000}	9.5	71.6c
$T_{1333/3}$	9.6	54.2bc
$T_{1000/3}$	9.9	44.7ab
$T_{667/3}$	10.5	29.1a
Dong Nai (4.9 yr)		
NT_{1111}	9.9	57.9a
$T_{600/2}$	10.4	42.2b
$T_{600/3}$	10.4	48.7ab
$T_{800/2}T_{600/3}$	10.5	45.3b
b) Fertiliser		
Tuyen Quang (5.4 yr)		
F_0	7.6a	19.6
F_1	7.8ab	20.5
F_2	8.0b	21.4
Ba Vi-1 (5.9 yr)		
F_0	7.9a	26.5a
F_1	8.2a	26.3a
F_2	8.5b	30.9b
Ba Vi-2 (7.4 yr)		
F_0	10.1a	55.3a
F_1	10.4b	60.9b
F_2	10.6b	65.9b

Appendix Table 4.3 Summary of analysis of variance showing the effects of thinning rate, fertiliser and their interaction on the distribution of two selected stem diameter classes for six experimental trials.

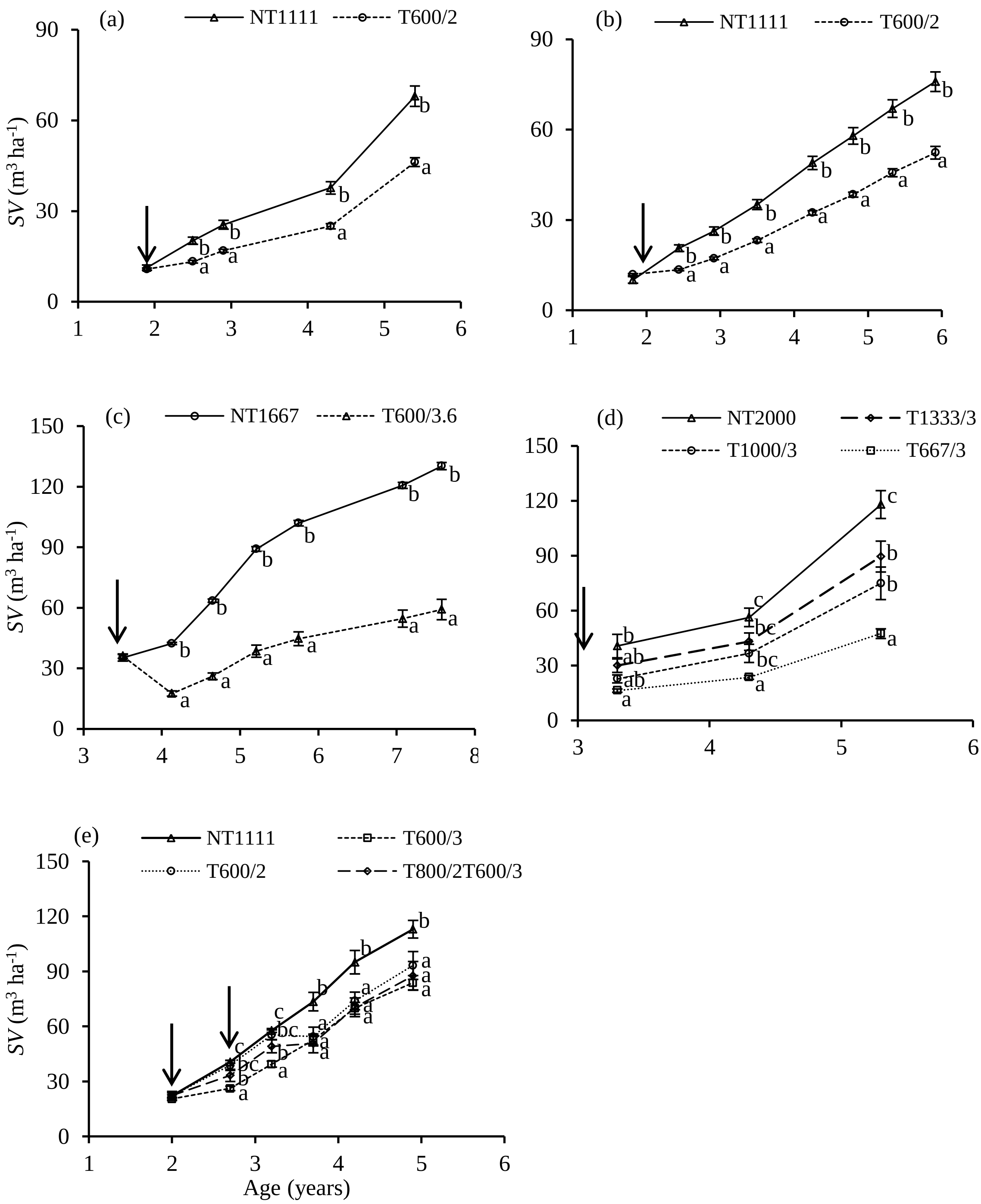
Trial	Effect	10 – 13.9 cm	14 – 17.9 cm
Tuyen Quang	Thinning intensity (T)	**	**
	Fertiliser (F)	*	*
	T × F	*	*
Ba Vi-1	T	***	***
	F	ns	ns (P = 0.073)
	T × F	*	ns
Ba Vi-2	T	***	***
	F	*	**
	T × F	ns	ns
Ba Vi-3	T	***	***
	Timing of thinning (t)	**	ns
	T × t	ns	ns
Binh Dinh	T	ns	ns
Dong Nai	T	*	ns (P = 0.062)

Appendix Table 4.4 Details of observed versus predicted regressions including regression coefficient (R^2), model efficiency (*EF*) and accuracy (*RMSE*) for *DBH* (cm) and *SV* (m^3 ha^{-1}) for a 15-yr rotation for all thinning and fertiliser treatments for each experimental trial. *N* = number of mean plots at each measurement.

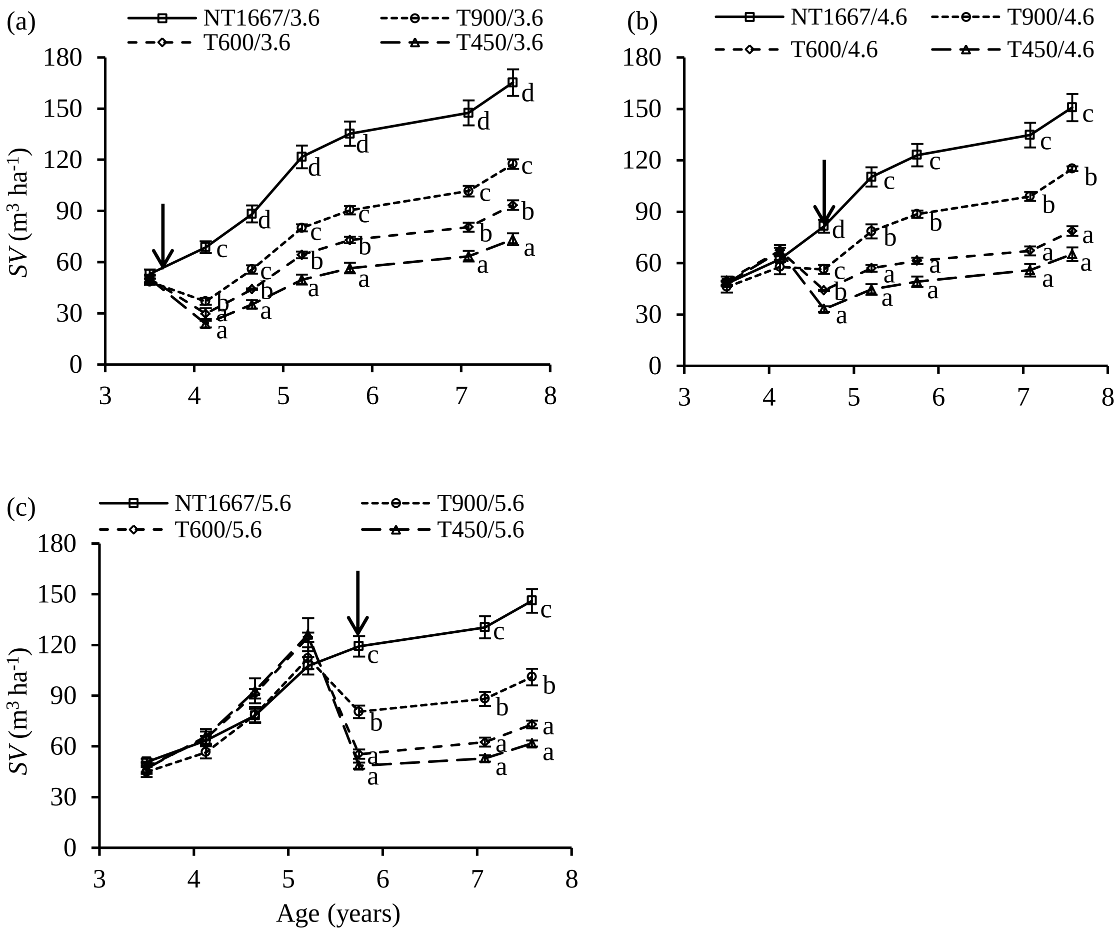
Trial/treatment	*N*	Slope		Intercept		R^2		*EF*		*RMSE*	
		DBH	*SV*	*DBH*	*SV*	*DBH*	*SV*	*DBH*	*SV*	*DBH*	*SV*
Tuyen Quang											
$NT_{1111}F_0$	7	1.65	1.26	-2.60	-5.32	0.98	0.97	0.62	0.88	1.40	9.12
$T_{600/2}F_0$	7	1.40	1.53	-4.12	-7.44	0.96	0.99	0.67	0.94	1.30	18.5
$NT_{1111}F_1$	7	1.31	1.32	-2.31	-4.02	0.72	0.96	0.68	0.78	1.47	9.30
$T_{600/2}F_1$	7	1.15	1.34	-2.98	-5.13	0.96	0.99	0.66	0.85	1.48	7.79
$NT_{1111}F_2$	7	1.51	1.30	-4.73	-4.09	0.97	0.96	0.65	0.81	1.51	9.10
$T_{600/2}F_2$	7	0.98	1.43	-1.39	-5.39	0.97	0.99	0.64	0.74	1.66	7.16
Ba Vi-1											
$NT_{1111}F_0$	7	0.71	0.85	2.61	13.91	0.97	0.96	0.95	0.94	1.08	24.90
$T_{600/2}F_0$	7	0.85	1.07	1.72	5.79	0.97	0.98	0.96	0.89	1.36	17.00
$NT_{1111}F_1$	7	0.99	1.23	0.33	-4.94	0.94	0.96	0.94	0.80	1.65	15.00
$T_{600/2}F_1$	7	1.04	1.33	-0.37	-5.72	0.94	0.97	0.93	0.67	1.83	12.95
$NT_{1111}F_2$	7	0.75	0.94	2.32	11.25	0.96	0.95	0.86	0.93	1.05	23.02
$T_{600/2}F_2$	7	0.83	1.01	1.53	4.28	0.94	0.91	0.89	0.86	1.24	10.61
Ba Vi-2											
$NT_{1667}F_0$	7	1.05	1.27	-0.46	-8.36	0.90	0.93	0.87	0.63	1.27	5.23
$T_{600/3.6}F_0$	7	0.78	1.23	2.04	-9.06	0.95	0.96	0.93	0.75	1.39	1.88
$NT_{1667}F_1$	7	0.78	0.99	2.04	8.63	0.95	0.94	0.88	0.89	0.97	21.25
$T_{600/3.6}F_1$	7	0.80	0.67	2.04	25.81	0.87	0.84	0.85	0.71	1.14	13.79
$NT_{1667}F_2$	7	0.84	0.76	1.44	26.30	0.84	0.82	0.82	0.80	1.26	11.63
$T_{600/3.6}F_2$	7	0.89	0.69	0.74	20.06	0.84	0.89	0.79	0.85	1.25	9.68
Ba Vi-3											
$NT_{1667/3.6}F_0$	7	0.64	0.76	3.14	17.47	0.98	0.98	0.81	0.98	0.99	19.02
$T_{900/3.6}F_0$	7	1.03	1.65	-0.04	-0.85	0.96	0.99	0.95	0.84	1.18	2.05
$T_{600/3.6}F_0$	7	0.57	0.71	3.92	23.57	0.98	0.97	0.72	0.89	1.20	23.50
$T_{450/3.6}F_0$	7	0.93	1.11	1.39	0.91	0.99	0.99	0.93	0.70	1.36	4.02
$NT_{1667/4.6}F_0$	7	0.66	0.83	3.15	17.91	0.97	0.97	0.86	0.94	1.00	19.69
$T_{900/4.6}F_0$	7	0.98	1.25	0.65	-0.07	0.96	0.98	0.92	0.55	1.33	3.00
$T_{600/4.6}F_0$	9	1.63	1.39	-5.50	-8.18	0.99	0.98	0.67	0.75	1.18	10.00
$T_{450/4.6}F_0$	9	1.74	1.51	-6.91	-10.86	0.97	0.99	0.53	0.64	1.43	8.22
$NT_{1667/5.6}F_0$	9	1.37	1.32	-3.84	-8.81	0.98	0.97	0.76	0.87	1.37	11.93
$T_{900/5.6}F_0$	9	1.38	1.34	-3.78	-6.31	0.98	0.99	0.81	0.81	1.76	10.05
$T_{600/5.6}F_0$	9	1.50	1.62	-4.13	-3.21	0.96	0.99	0.74	0.85	1.27	10.96
$T_{450/5.6}F_0$	9	1.55	1.38	-5.26	-7.26	0.94	0.99	0.67	0.77	1.59	9.41
Binh Dinh											
$NT_{2000}F_0$	7	0.57	0.71	4.18	28.72	0.95	0.96	0.78	0.89	1.46	27.71
$T_{1333/3}F_0$	7	0.55	0.76	3.74	30.65	0.96	0.98	0.60	0.84	1.52	22.28
$T_{1000/3}F_0$	7	0.73	0.70	2.39	28.34	0.98	0.95	0.86	0.81	1.68	19.90
$T_{667/3}F_0$	7	0.80	1.15	1.89	5.32	0.98	0.70	0.92	0.75	1.95	14.36
Dong Nai											
$NT_{1111}F_0$	7	0.95	1.00	-0.31	-4.07	0.99	0.99	0.94	0.98	2.35	20.65
$T_{600/2}F_0$	7	0.92	1.01	1.39	-5.84	0.91	0.98	0.95	0.93	2.48	13.96
$T_{600/3}F_0$	7	0.95	1.02	-0.48	-8.59	0.99	0.96	0.91	0.86	2.48	15.00
$T_{800/2}T_{600/3}F_0$	7	0.98	0.94	-0.53	-8.11	0.99	0.94	0.95	0.78	2.45	16.22



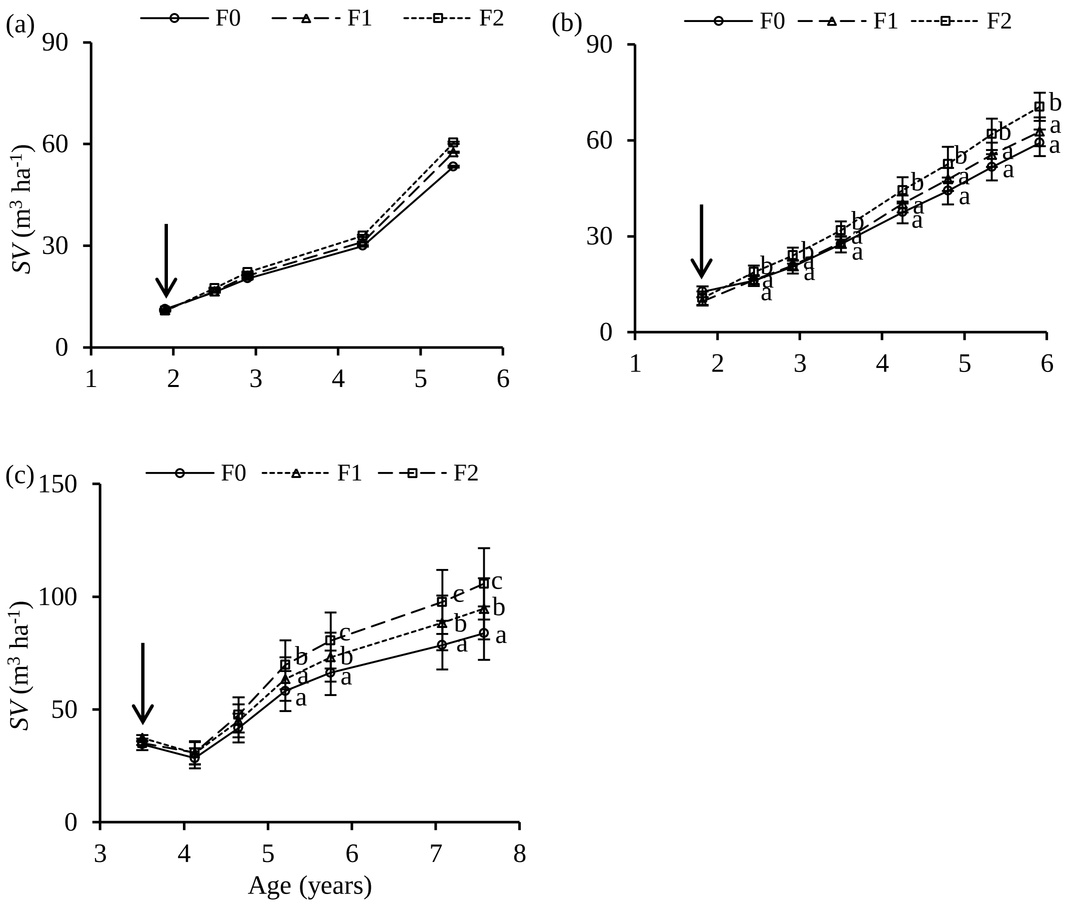
Appendix Figure 4.1 Location of the six experimental trials in Vietnam.



Appendix Figure 4.2 Effect of thinning intensity × tree age interaction on *SV* (m^3 ha^{-1}) at Tuyen Quang (a), Ba Vi-1 (b), Ba Vi-2 (c), Binh Dinh (d) and Dong Nai (e). Different letters indicate that means are significantly different at P <0.05 within a measurement period. Arrows indicate the timing of thinning. See Table 2 for codes and description of treatments.



Appendix Figure 4.3 Effects of thinning intensity × timing of thinning x tree age interaction on *SV* (m^3 ha^{-1}) at three sites in Ba Vi-3. Different letters indicate that means are significantly different at $P < 0.05$ within a measurement period. Arrows indicate the timing of thinning. See Table 2 for codes and description of treatments.



Appendix Figure 4.4 Effect of fertiliser-at-thinning application × tree age interaction on *SV* (m^3 ha^{-1}) at Tuyen Quang (a), Ba Vi-1 (b) and Ba Vi-2 (c). Different letters indicate that means are significantly different at P <0.05 within a measurement period. Arrows indicate the timing of fertiliser application. See Table 2 for codes and description of treatments.

Fertiliser application at thinning at Ba Vi site.

Early-age thinning at age 2 years at Tuyen Quang.

CHAPTER 5

COMPARISION OF SOIL PROPERTIES UNDER TROPICAL *ACACIA* HYBRID PLANTATION AND SHIFTING CULTIVATION LAND USE IN NORTHERN VIETNAM

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CHAPTER 5. COMPARISION OF SOIL PROPERTIES UNDER TROPICAL *ACACIA* HYBRID PLANTATION AND SHIFTING CULTIVATION LAND USE IN NORTHERN VIETNAM

Abstract

Despite the common use of *Acacia* species in Vietnam, few studies have examined changes to total soil nitrogen (TN) and total soil carbon (TC) following the planting of *Acacia auriculiformis* × *A. mangium* (*Acacia* hybrid) plantations (AH) on formerly eroded and degraded soils. We compared the impact of AH with adjacent fallow land within a shifting cultivation system (FSC) on various soil properties including TC, TN, pH, bulk densities and particle-size distribution in 10 cm increments down to 30 cm for 25 paired sites in northern Vietnam. The results show that TN and TC concentrations in AH were significantly higher at all 10 cm depth increments when compared to FSC. While both TC and TN decreased significantly with depth under both land uses, the C/N ratio only decreased in AH and not the FSC. However, there was a significant decrease in soil pH in AH at all depths (>0.4 pH units) and this may potentially cause acid infertility issues. While the study has shown that planting *Acacia* hybrid is an excellent option for the improvement of TN and TC on degraded acidic Acrisols, mitigation of the associated acidification may be required.

Keywords: degraded acidic Acrisols, total soil nitrogen, soil organic carbon, soil depth, land use

5.1. Introduction

In Vietnam, deforestation from extensive 'slash and burn' cultivation and subsequent unsustainable land use practices have resulted in widespread soil degradation (i.e. erosion, nutrient and organic matter decline) with 9.4 Mha classed as degraded land (Lamb, 2011; Dong et al., 2014). In 1998, the Five Million Hectares Rehabilitation Program (5MHRP) was launched in an attempt to restore forest coverage back to 43% (MARD, 2001; Phat, 2011). Since then, reforestation and farm forestry have contributed to diversifying incomes for smallholders and providing some of the goods and services required by these communities (Nambiar et al., 2015).

The majority of the studies examining the restoration of degraded forests or fallow lands within the shifting cultivation system (slash-and-burn or swidden agriculture) by either plantation or natural forest (Vien et al., 2001; Do et al., 2005; Woo et al., 2011) have highlighted the challenges of restoring degraded areas using native species due their intolerance of infertile soils and a lack of understanding of their physiology (Hung et al., 2010). Northern Vietnam is dominated by Acrisols, which are characterised by deeply weathered acid profiles with low base saturation to depth and low activity clays with low to moderate natural fertility (Phuong et al., 2012; Sang et al., 2013). In this respect, leguminous *Acacia* plantations may be useful because they are fast-growing, can produce commercially useful goods, and can improve N fertility by their ability to fix N_2. They are also tolerant of a variety of poor acidic and leached soils and can potentially improve these through carbon and nitrogen additions (Sang et al., 2013; Dong et al., 2014).

There have only been a few studies that have examined the effect of land use on soil properties including total soil carbon (TC), total soil nitrogen (TN) and soil pH in Vietnam (Que et al., 2010; Sang et al., 2013; Anh et al., 2014; Dong et al., 2014). In terms of TC, these studies have shown that *Acacia* plantations improve TC more than other land uses including grassland, secondary forest and abandoned land (Sang et al., 2013; Anh et al., 2014; Dong et al., 2014). For example, in a chronosequence study, Dong et al. (2014) showed significantly higher TC in second and third rotation *Acacia* hybrid plantations compared with adjacent abandoned sites in central Vietnam. This difference was attributed to the larger biomass production of forest cover compared to the abandoned agricultural lands (Dong et al., 2014). In a recent plot-scale study comparing the soil properties of major land-use types in northern Vietnam, the TC of *Acacia* species was significantly higher than any of the other nine land uses with the exception of lemon-grass land use (Anh et al., 2014). However, in contrast to these findings, Sang et al. (2013) showed that TC concentration was similar for *A. mangium* plantations, secondary forest and pasture land use in both northern and southern Vietnam.

Previous studies examining the effect of land use on soil N have shown that *Acacia* plantations can improve soil N compared with other land uses, most likely reflecting the capacity of *Acacia* species to fix atmospheric N_2 (Macedo et al., 2008; Kasongo et al., 2009; Yang et al., 2009; Dong et al., 2014). For example, Dong et al. (2014) found that soil N of *A.* hybrid in the first and second year of rotation (1.7 and 1.5 Mg ha^{-1}, respectively) was significantly higher than corresponding abandoned land (1.0 Mg ha^{-1}). Similarly, *Acacia* species had the highest soil N compared with other land-uses including bare soil, agriculture (cassava or lemon grass), shrub land, five types of plantation forest, and indigenous forest in northern Vietnam (Anh et al., 2014). In contrast, soil N was reported to be similar for *A. mangium* plantation (3 – 17 years old), secondary forest and pasture land uses across Vietnam (Sang et al., 2013). Yamashita et al. (2008) showed that soil N in the 0 – 20 cm soil layer was not significantly different between 8 year old *A. mangium* plantation, secondary forest and *Imperata* grassland in South Indonesia.

There remain uncertainties in our understanding of how *Acacia* plantations impact soil acidity in Vietnam. The limited information suggests that *Acacia* hybrid can be grown on degraded soils with pH_{KCl} values as low as 3.5 on a wide range of sandy to clay soils, particularly in central and southern Vietnam (Que et al., 2010). There is some concern that soil pH is reduced under *Acacia* plantations as compared to other land uses (Macedo et al., 2008; Kasongo et al., 2009; Yang et al., 2009; Sang et al., 2013; Dong et al., 2014). For example, the soil pH of 5-year-old *Acacia* hybrid in central Vietnam was lower than adjacent abandoned lands by 0.2 pH units in the 0 – 20 cm layers (Dong et al., 2014). Similarly, the soil pH of *A. mangium* and *E. urophylla* plantations (pH = 4.4) across Vietnam was significantly lower compared to nearby secondary forest (pH = 4.5) and pasture soil (pH = 4.9) (Sang et al., 2013). (Yamashita et al., 2008) found significantly lower soil pH in *A. mangium* plantations and secondary forests than in *Imperata* grassland for all soil depths (from 0 to 30 cm) in South Indonesia. (Yamashita et al., 2008) suggested that the soil acidity was partly due to the lower base saturation associated with a lower amount of exchangeable base cations under *Acacia* plantations.

In Vietnam, there is a paucity of published research on TC and TN changes with depth under both *Acacia* hybrid plantations (hereafter referred to as AH) and fallow land within shifting cultivation system (hereafter referred to as FSC). In the mountainous regions of Vietnam, shifting cultivation has been commonly practiced for centuries by 54 ethnic minorities, mainly H'Mong and Dao groups, across an area of 3.5 million ha (Sam, 1994; Do et al., 2011). Under the pressures of increasing populations and land scarcity, this traditional shifting cultivation system has changed (from short cultivation – long fallow periods to long cultivation – short fallow periods) resulting in increased soil erosion and a decline in soil fertility (Vien et al., 2001; Wezel et al., 2002; Do et al., 2011). The purpose of this study was to determine TC and TN in 10 cm increments down to 30 cm under both AH and FSC in northern Vietnam. We hypothesized that the TC, TN and pH of AH will be different to FSC. Such research information is needed for land management decisions made by foresters and farmers.

5.2. Materials and methods

5.2.1. Study sites

The study sites (Figure 5.1) were located in Ham Yen district of Tuyen Quang province in northern Vietnam (Lat. 21.7° N, Long. 105.2° E). The climate is tropical with four distinct seasons. The summer is hot and rainy and affected by the north-west monsoon, and the winter is cold and dry; the mean monthly maximum temperature is 28 °C, the minimum is 16 °C, the mean annual rainfall, concentrated between May and September, is 1650 mm and the monthly rainfall varies between 16.0 – 311.7 mm (Tuyen Quang Weather Station) (Figure 5.2). These sites were located on sloping land (>30%) with shallow (*ca* 50 cm) lateritized (deeply weathered) Acrisols of low fertility (acidic and leached).

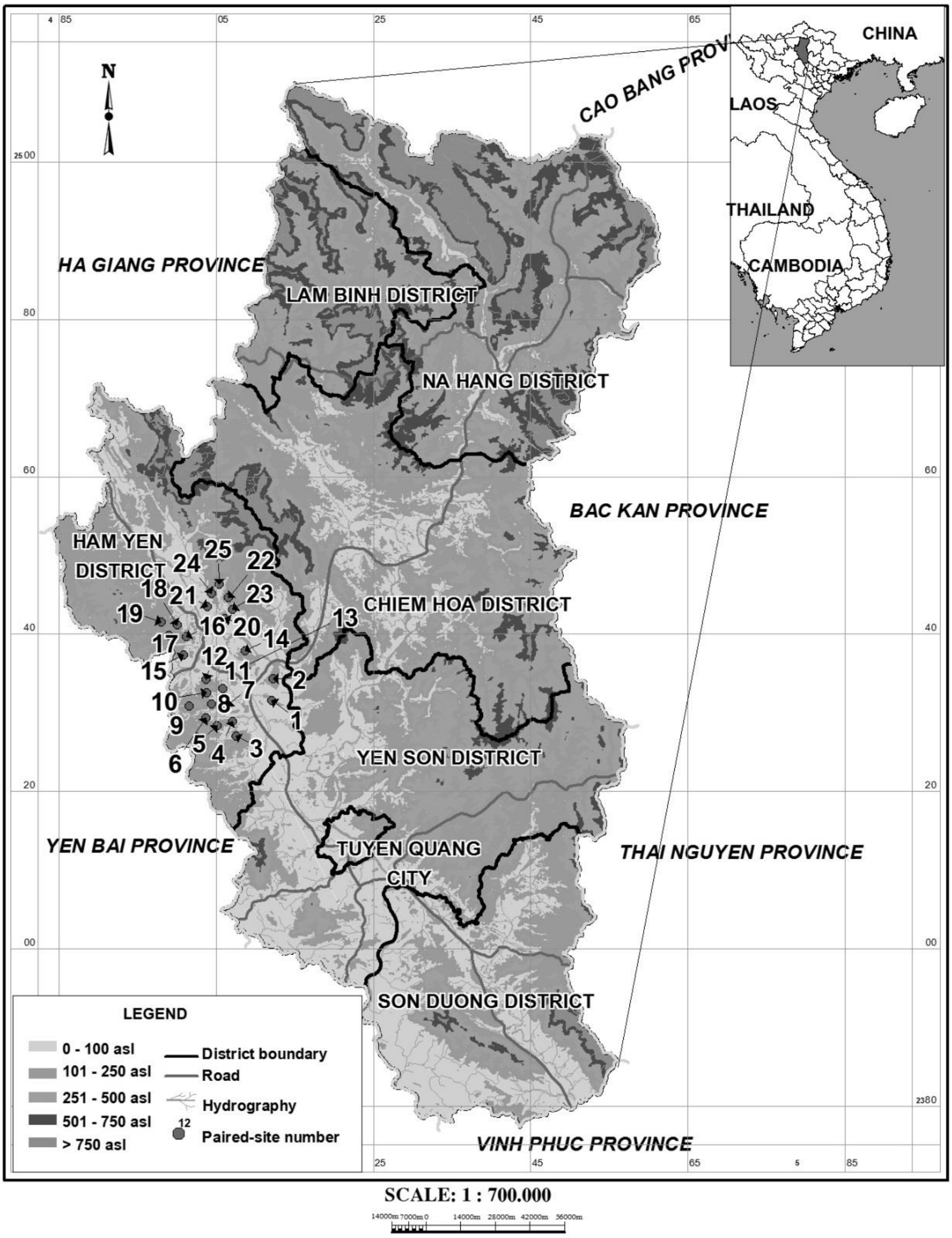

Figure 5.1 Map of study area and location of *Acacia* hybrid plantations (AH) and fallow land within shifting cultivation (FSC) sites in northern Vietnam. Each point represents where a paired plot with a plot on the AH land use and a plot on the FSC land use.

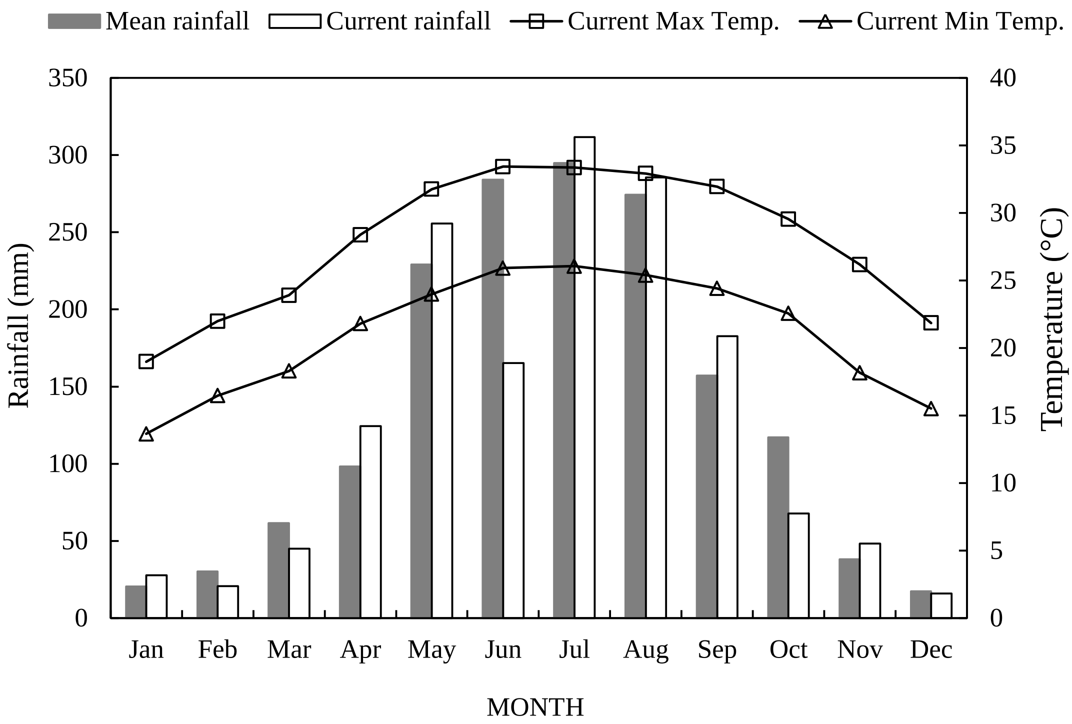

Figure 5.2 Mean long-term monthly rainfall for the period 1970 – 2005 and current mean monthly rainfall and current maximum and minimum temperature for the period 2006 – 2014 of the study area in northern Vietnam.

This study focussed on two major land uses around Ham Yen district of Tuyen Quang provinces: (1) second-rotation *Acacia* hybrid plantations established between 2006 and 2007 and (2) adjacent fallow land within shifting cultivation system managed in short rotation cycles typically of 1 – 3 years. The history and current management practices for each land use are described in Table 5.1. *Acacia* hybrid plantations managed for pulpwood production were aged 5 – 6 years and planting densities ranged from 1111 to 2500 trees ha^{-1} (areas of 2 – 4 ha), with diameter at breast height at 1.3 m above ground surface (*DBH*) ranging from 11.1 to 16.9 cm, total height (*H*) from 11.4 to 18.0 m, basal area (*BA*) from 9.5 to 29.6 m^2 ha^{-1}, standing volume (*SV*) from 111.5 to 147.8 m^3 ha^{-1} and mean annual increment (*MAI*) from 10.6 to 23.4 m^3 ha^{-1} yr^{-1}. For FSC land use, the land is prepared by slash and burn techniques applied from January to

March followed by cultivation. Planting typically occurs in April and harvesting from mid-December to January. The land is left to fallow only when the crops grow poorly i.e., their yield reduces to 20 – 30% of that of the first cultivation year, due to carbon and nutrient depletion in the soil (Vien et al. 2001; Do et al. 2011). The fallow period may last 1 to 3 years to allow the site to recover as it reverts to shrub land dominated by *Imperata cylindrica* and *Rhodomytus tomentosa*. In some cases, the FSC is replaced with permanent cropping (mainly rice, maize or cassava).

A total of 25 paired sites with AH and FSC were selected. Each plot of the paired plots were located between 90 – 160 m of each other to be representative of the same environmental factors i.e., similar topography, soil types and properties, geology and climate.

Table 5.1 Summary of the history and current management practices of *Acacia* hybrid plantations (AH) and fallow land within shifting cultivation (FSC) land uses used in the study.

	Acacia hybrid plantations (AH)	Fallow land within shifting cultivation (FSC)
History		
1940 – 1960	Evergreen broad-leaved forests	Evergreen broad-leaved forests
1960 – 1980	Secondary forests or shifting cultivation	Secondary forests or shifting cultivation
1990 – 2000	Either reforested secondary forests or shifting cultivation to timber-producing forests, plantation land use (mainly *A. mangium*)	Shifting cultivation land use
2000 to date	plantation land use (*A. mangium* and *Acacia* hybrid)	Shifting cultivation land use
Current management practices		
Site preparation	Burn litter and slash from previous rotation	Slash and burn from January to March after yearly harvest
Planting	June-July 2005 and 2006	Annually April
Crop	Mixture of *A.* hybrid clones (BV 10, BV 16 and BV 32)	Either paddy rice, maize or cassava in a 5 – 7 year crop rotation that includes a fallow period of 1 – 3 years
Fertiliser	0.1 – 0.2 kg 5:10:3 N:P:K tree^{-1} at planting	50 – 100 kg 5:10:3 N:P:K ha^{-1} 3 months after cultivation
Harvested	Rotation of 6 – 7 years	Annually from mid-December to January

5.2.2. Soil sampling

Soil was sampled in the dry season from September 2012 to January 2013. Three sample plots (20 m × 20 m) were randomly established in each of the 25 paired AH and FSC sites. For AH sites, the plots were used for both soil sampling and measurements of tree growth, while only the soil was sampled in the FSC sites. A paired sampling approach was undertaken to evaluate soil properties associated with AH and FSC land uses. The main assumption of this method is that the sampled soils belong to the same soil series (all Acrisols), and that any differences in soil properties can be attributed to different land uses. In each plot, soil samples for chemical analysis were collected randomly at five different sampling points using a 100 mm diameter auger at 10 cm intervals to 30 cm. Guidelines from the IPCC (2003) recommend that soil sampling to a depth of 30 cm is appropriate for TC sampling. The surface 0 – 5 cm soil depth has the highest concentration of soil organic carbon and nutrients (Gonçalves et al., 2008; Smith et al., 2008) and is the most sensitive to disturbance by land use practices (Batjes, 1996; Hurtt et al., 2006; Bationo et al., 2007). The five samples were pooled to provide a composite soil sample for each depth. This procedure was replicated three times for each plot (total of 450 samples). The litter layer was carefully removed before sampling the mineral topsoil for analysis. In order to minimise any disturbance from site preparation and silvicultural practices at AH sites, the sampling points were placed in the centre of the inter-row trees. The sampling points in the FSC sites were selected from fallow areas within the 20 m plots. For soil bulk density (BD) sampling, further samples were collected from each of the 25 paired sites. Two replicate cores were taken from the centre of each of the three 10 cm sampling depth intervals (total of 150 core samples) using a 53 mm diameter × 51 mm length cylinder. Soils were classified according to the Soil World Reference Base framework (FAO, 2006).

5.2.3. Soil physical and chemical properties

Soil samples were air-dried, lightly milled and sieved to <2 mm, followed by oven drying at 65 °C to constant weight. Soil BD was determined from cores that had been dried at 105 °C to constant weight. Gravel (>2 mm) in each BD core was separated and weighed. Preparation and chemical analysis of the composite soil samples followed the Australian Laboratory Handbook of Soil and Water Chemical Methods (Rayment and Higgingson, 1992). Soil pH was measured with a handheld Laboratory Navigator (Forston Labs, Fort Collins, CO, USA) in a 1:5 mixture of soil and either distilled water (pH_{H_2O}) or 1M potassium chloride (pH_{KCl}). Total soil carbon (TC) and total nitrogen (TN) were determined using a CHN/O Element Analyser (Perkin-Elmer Inc., Waltham, MA, USA). As these soils are acidic and non-calcareous TC will be equivalent with total organic carbon (TOC).

5.2.4. Particle size analysis

Soil sub-samples were dispersed by end-over-end shaking in a 0.5 M Na-hexametaphosphate solution for 16 h. Soil was then passed through a 50 µm sieve to separate the sand from silt and clay fractions. The coarser fraction was then dried, weighed and sieved while the finer fraction (clay + silt) was determined by pipette based sedimentation methods. No chemical pre-treatment was used to remove organic matter, carbonates or iron oxides as the soils are low carbon, very acidic, non-calcareous and low in iron oxides. All data are reported as unit per oven-dried weight for sand, silt and clay.

5.2.5. Growth measurement in plantations

The *DBH* (cm) and *H* (m) of a total of 30 trees were measured in each plantation plot. The stem volume (V, m^3 $tree^{-1}$) for each individual stem measured was calculated across all sites using the following equation:

$$V = \frac{\pi}{4} \times DBH^2 \times H \times f \qquad (1)$$

where f is a stem form factor (f = 0.495) (Binh, 2003) The volume of a plot was then scaled to a per hectare basis (m^3 ha^{-1}). The *BA* (m^2 ha^{-1}) of a plot was calculated as the sum of the cross sectional area over bark at breast height of all individuals in each plot and scaled to a per hectare basis. The *MAI* (m^3 ha^{-1} yr^{-1}) of individual plots was calculated by dividing the *SV* of a plot by stand age.

5.2.6. Statistical analysis

The stocks of TC or TN (Mg ha^{-1}) for each soil depth (0 – 30 cm) were calculated as Batjes (1996):

$$\text{Stock of TC or TN (Mg ha}^{-1}) = \text{Content}_{layer} \text{ (g kg}^{-1}) \times \text{BD}_{layer} \text{ (g cm}^{-3}) \times \text{Soil depth (m)} \times 10^{-3} \text{ Mg kg}^{-1} \times 10^{4} \text{ m}^2 \text{ ha}^{-1} \qquad (2)$$

Determination of BD was measured in the <2 mm fraction only. As such, the gravel weight was removed from the calculation of carbon stock per ha. Effect of land use types and soil depth on soil properties were examined by a split-plot analysis of variance (ANOVA). The land use type was the main plot factor while the soil depth was the subplot factor. Fisher's protected least significant difference post hoc test (LSD at P <0.05) was used to determine specific differences between treatment means of the two land use types. Pearson correlations coefficients were used to detect relationships among soil variables at P <0.05. Linear regression analysis was used to examine the relationships among all soil and growth parameters of the AH land use. All analyses were performed in Genstat 13th Edition (VSN Int., Hemel Hempstead, UK).

5.3. Results

5.3.1. Soil properties

Land use and soil depth significantly influenced both pH_{H_2O} and pH_{KCl} in the same way therefore only the pH_{H_2O} data (Table 5.2) are discussed, though the pH_{KCl} values are also given in Table 2. Soil pH_{H_2O} was found to be significantly affected by land use and soil depth. Soil pH_{H_2O} was approximately 0.4 – 0.5 units lower under AH as compared to FSC at each soil depth. Soil pH_{H_2O} generally increased with depth under both land uses. Soil pH_{H_2O} of AH only varied from 3.7 to 3.9 with increasing soil depth while under the FSC, the soil pH_{H_2O} ranged from 4.2 to 4.3.

There was no significant difference in BD between AH and FSC or depth (Table 5.2). Soil BD in AH ranged from 1.2 to 1.3 g cm^{-3} while the FSC sites ranged from 1.3

to 1.4 g cm^{-3}. Soil particle size analysis showed that clay but not gravel, sand and silt % was significantly affected by land use. FSC had significantly higher clay % than AH throughout the profile (Table 5.2). The dominant particle fraction of the <2 mm fraction for both land use types was silt (50 – 60%), while clay ranged from 20 – 28%.

Table 5.2 Some soil properties associated with soil depth under *Acacia* hybrid plantations (AH) and fallow land within shifting cultivation (FSC) sites in northern Vietnam (mean ± SE, n = 25).

Variables	Depth (cm)	Land use		*P* values
		Acacia hybrid	Degraded land	
pH_{H_2O}	0 – 10	3.7 ± 0.03	4.2 ± 0.03	***
	10 – 20	3.8 ± 0.02	4.3 ± 0.03	***
	20 – 30	3.9 ± 0.05	4.3 ± 0.03	***
pH_{KCl}	0 – 10	3.2 ± 0.07	3.7 ± 0.03	***
	10 – 20	3.2 ± 0.05	3.6 ± 0.03	***
	20 – 30	3.3 ± 0.05	3.6 ± 0.03	***
BD (g cm^{-3})	0 – 10	1.2 ± 0.03	1.3 ± 0.04	ns
	10 – 20	1.3 ± 0.03	1.3 ± 0.03	ns
	20 – 30	1.3 ± 0.02	1.4 ± 0.03	ns
Clay (%)	0 – 10	26.5 ± 0.69	22.5 ± 0.69	*
	10 – 20	28.5 ± 0.89	24.7 ± 0.60	*
	20 – 30	28.6 ± 0.89	18.3 ± 3.01	*
Silt (%)	0 – 10	52.8 ± 1.03	50.0 ± 2.03	ns
	10 – 20	51.8 ± 1.64	51.6 ± 1.80	ns
	20 – 30	51.6 ± 1.64	60.8 ± 1.80	ns
Sand (%)	0 – 10	20.7 ± 1.26	27.5 ± 0.97	ns
	10 – 20	19.7 ± 1.94	23.7 ± 0.96	ns
	20 – 30	19.8 ± 1.91	20.9 ± 0.97	ns
Gravel (%)	0 – 10	7.1 ± 1.46	8.1 ± 1.72	ns
	10 – 20	6.9 ± 2.44	7.3 ± 2.13	ns
	20 – 30	7.6 ± 2.62	8.4 ± 1.59	ns

ns = not significant; * = P <0.05; *** = P <0.001

Total soil nitrogen concentration was significantly higher in the AH plots at all depths measured to 30 cm (Figure 5.3a). At all soil depths, the TN under AH was significantly higher (1.5, 1.2 and 1.1 g kg^{-1}) compared to FSC (1.1, 0.8 and 0.6 g kg^{-1}). In terms of TN stocks, AH was significantly higher than FSC for the 0 – 30 cm soil depth (3.8 *v.s* 2.5 Mg ha^{-1} respectively, P <0.05).

The concentration of TC was significantly higher under AH and it decreased with depth for both land use types (Figure 5.3b). The effect of land use was most pronounced in the upper 0 – 10 cm but continued to 30 cm, with the AH being consistently higher than the FSC plots. Specifically, the concentrations of TC in AH were 16.6, 11.5 and 9.1 g kg^{-1} compared to 3.7, 10.4 and 8.8 g kg^{-1} in FSC at 10 cm intervals to 30 cm, respectively. In terms of stock C, AH was significantly higher than FSC for soil depth to 30 cm (37.2 and 32.7 Mg ha^{-1} respectively, P <0.05).

The soil C/N ratios varied significantly among soil depths and land use. Specifically, the soil C/N ratios for AH were lower at all soil depth intervals than in FSC (Figure 5.3c). Under AH, the soil C/N ratios declined from 11.2 to 8.4 with soil depth to 30 cm. In contrast, soil C/N ratios of FSC tended to be constant and then increased with soil depth, with 12.9, 12.6 and 14.2 at 0 – 10, 10 – 20 and 20 – 30 cm, respectively.

Strong significant correlations were found between TC, TN and pH_{H_2O} under AH, but under FSC, only the relationship between TN and TC was significant (Table 5.3).

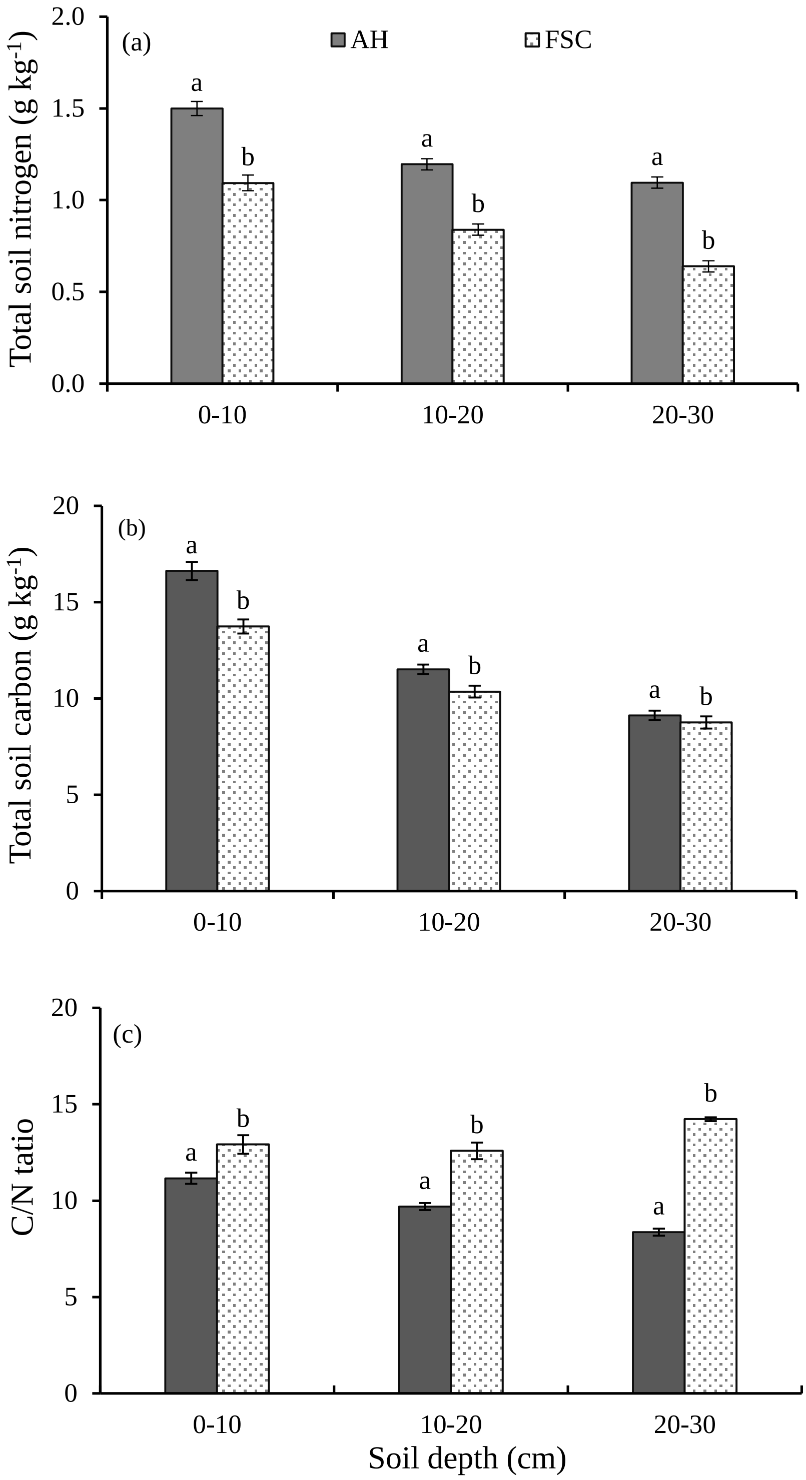

Figure 5.3 Comparison of mean (± SE, n = 25) total soil nitrogen (a), total soil carbon (b) and C/N ratio (c) at three soil depths between *Acacia* hybrid plantations (AH) and fallow land within shifting cultivation (FSC) land uses. Different letters within a soil parameter denote significant differences between treatment means (P <0.05).

Table 5.3 Pearson correlation among soil properties of *Acacia* hybrid plantations (AH) and fallow land within shifting cultivation (FSC) in northern Vietnam.

		SOC (g kg^{-1})	TN (g kg^{-1})	pH$_{H_2O}$	Clay (%)
AH land use	TN (g kg^{-1})	0.83***			
	pH$_{H_2O}$	-0.63***	-0.61***		
	Clay (%)	-0.06^{ns}	-0.08^{ns}	0.19^{ns}	
	BD (g cm^{-3})	-0.27*	-0.25*	-0.01^{ns}	-0.24*
FSC land use	TN (g kg^{-1})	0.75***			
	pH$_{H_2O}$	0.02^{ns}	0.22^{ns}		
	Clay (%)	-0.21^{ns}	-0.25*	0.18^{ns}	
	BD (g cm^{-3})	-0.05^{ns}	-0.04^{ns}	0.06^{ns}	0.01^{ns}

ns = not significant; * = P <0.05; *** = P <0.001

5.3.2. Relationships between AH productivity (*MAI*) and soil properties

The *MAI* ranged between 10.6 and 23.4 m^3 ha^{-1} yr^{-1} and was significantly affected by stocking rate (1111 trees ha^{-1}: 22.2 ± 0.32 m^3 ha^{-1} yr^{-1}; 1667 trees ha^{-1}: 16.6 ± 0.34 m^3 ha^{-1} yr^{-1}; 2000 trees ha^{-1}: 13.8 ± 0.75 m^3 ha^{-1} yr^{-1}, P < 0.001). There were significant positive relationships between *MAI* and TN, TC and soil pH$_{H_2O}$, in 0 – 10 cm of the top soil (Figure 5.4a, b, c).

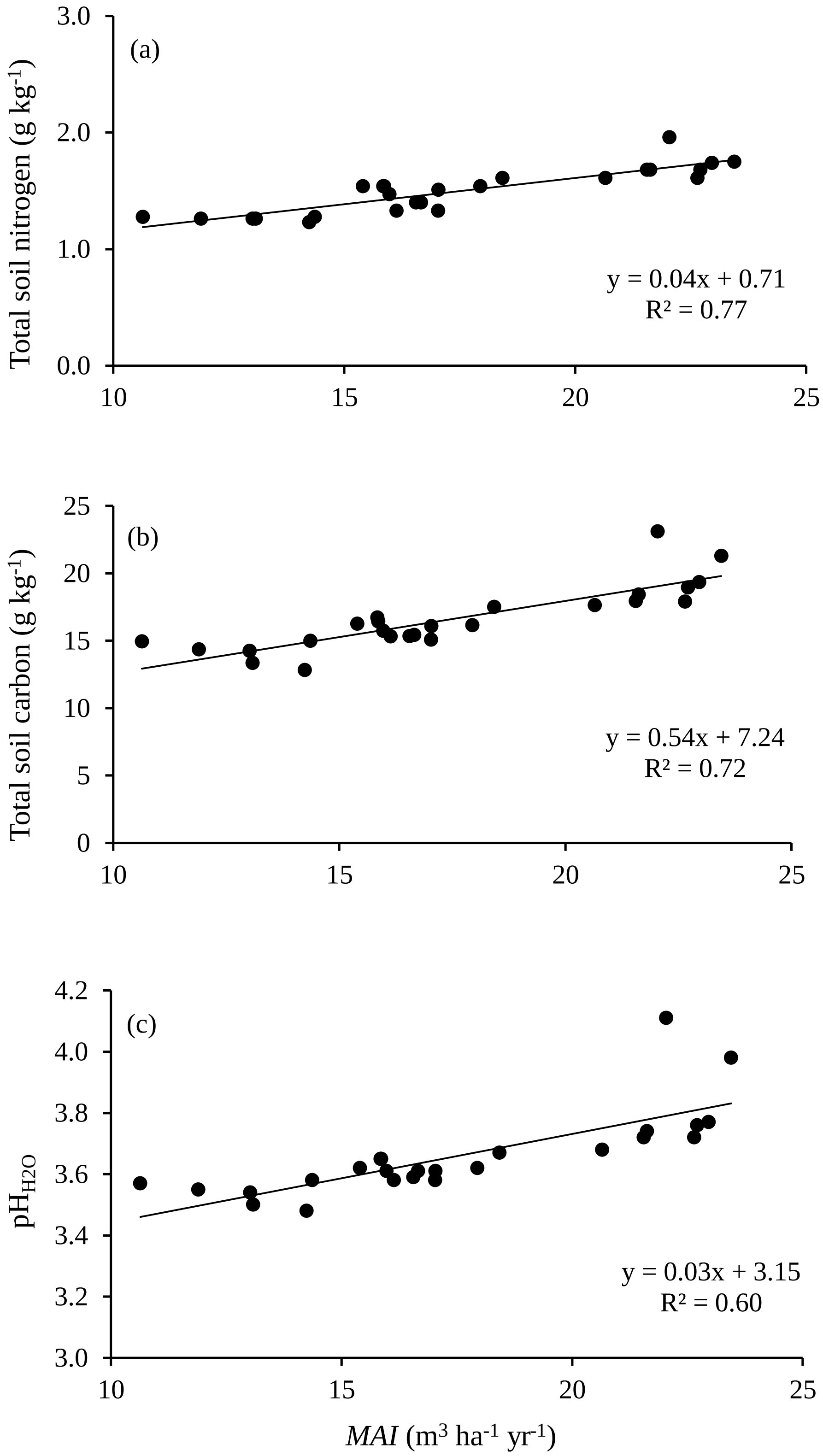

Figure 5.4 Relationships between mean annual increment (*MAI*) with total soil nitrogen (a), total soil carbon (b) and soil $\mathbf{pH_{H_2O}}$ (c) for 0 – 10 cm soil depth of *Acacia* hybrid plantations (AH).

Table 5.4 Comparison of selected published soil properties under different land uses in Vietnam.

Land use	Location	Soil type (FAO)	Age/length of time (year)	Soil depth (cm)	pH	SOC ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	C/N	References
A. mangium	North	Acrisols	4 – 17	0 – 10	4.4	18.9	1.9	10.0	Sang et al., 2013
A. auriculiformis	South	Chromic Acrisol	6	0 – 10	4.8	16.7	1.2	13.9	Huong et al., 2015
Acacia hybrid	North	Ferralic Acrisol		0 – 10	3.9	12-27	1.1-1.7	11 – 15.9	Beadle et al., 2013
	North	Ferralic Acrisol	5 – 6	0 – 10	3.7	16.6	1.5	11.2	This study
	Central	Acrisols	5	0 – 20	4.3	13.5	0.9	15.0	Dong et al., 2014
	South	Ferralic Acrisol		0 – 10	4.3	11.5 – 40	0.7 – 2.2	16 – 18	Beadle et al., 2013
Secondary forest	North	Ferralic Acrisol	8	0 – 10	4.5	18.2	1.8	10.1	Sang et al., 2013
Fallow land	North	Acrisols	9	0 – 10	4.9	17.3	1.6	10.8	Sang et al., 2013
	North	Ferralic Acrisol	1 – 3	0 – 10	4.2	13.7	1.1	12.9	This study
	Northeast	Acrisols	3 – 10	0 – 10	3.9 – 4.5	14.1 – 25	2.1 – 2.6	6.7 – 9.6	Thuong, 2003
Abandoned lands	Central	Acrisols	16	0 – 20	4.5	8.5	1.0	8.5	Dong et al., 2014

5.4. Discussion

The results from this study support previous findings that many Vietnamese soils that are considered as degraded are characterised by low soil pH, low concentrations of TC and TN. We found that both TC and TN concentrations were significantly higher under AH sites compared to neighbouring FSC sites.

Soil pH_{H_2O} was significantly lower under AH sites as compared to FSC sites at all depths, which supports previous findings that soil pH under *Acacia* plantations is generally lower than other land uses. For example, a lower pH was reported under *Acacia* plantations in Vietnam compared to pasture, abandoned land and secondary forest (Sang et al., 2013; Dong et al., 2014). Similarly, soil pH values were significantly lower under *A. auriculiformis* fallows (1 – 17 years) compared to virgin savannah composed of mainly *Loudetia arundinacea* and *Hyparrhenia diplandra* in the Congo (Kasongo et al., 2009).

Previous work has related the lower pH in *Acacia* plantations to many different factors such as soil type (Sang et al., 2013), base cation cycling (Yamashita et al., 2008), the removal of biomass (Yamashita et al., 2008; Dong et al., 2014), high nitrification (Li et al., 2001) and the release of organic acids from both live plants and decaying litterfall (Paul et al., 2003). Acrisols, which are the most common soil type in northern Vietnam, are strongly weathered acid clayey soils with low base saturation to depth (Sang et al., 2013). In such base cation limited soils, any increases in soil organic matter (SOM) will increase the size of the exchange complex, an outcome shown to lower soil pH (Binkley, 1992).

Not all authors report a decrease in soil pH under *Acacia*. Soil pH values for *A. mangium* in Indonesia and *A. auriculiformis* in South Vietnam remained unchanged throughout a second rotation of these *Acacia* species (Huong et al., 2008; Siregar et al., 2008; Hardiyanto and Nambiar, 2014). The authors attributed the lack of significant changes in soil pH to the retention of slash which may mitigate against the loss of exchangeable cations from the surface soil by leaching. (Nambiar and Harwood, 2014) in their review of short-rotation *Acacia* plantations in SE Asia, state that *Acacia* plantations do not cause soil acidification and that design factors like site history and sampling protocols may have confounded the results of other authors. They suggest that this controversy over acidification under *Acacia* can only be solved by controlled experiments over multiple rotations that regularly monitor the impacts of silvicultural management on soils. Also warranting further investigation is our observation that an increase in soil pH, however slight, can significantly improve *MAI* in AH and if so, whether it is feasible to manage soil pH.

Total soil nitrogen values measured in this study were similar to those reported in other studies in Vietnam (Table 5.4). We found the levels of TN in AH sites were significantly higher (16 – 26%) compared to FSC sites at all depths measured to 30 cm. This result is consistent with previous studies that compared TN levels in tropical *Acacia* plantations with other land uses in the Congo, South China and Vietnam (Kasongo et al., 2009; Yang et al., 2009; Dong et al., 2014). The high concentrations of TN under *Acacia* have been related to this species' ability to fix atmospheric N through symbiosis with root nodulating bacteria (*Rhizobium* and *Bradyearhizobium*) (Giller, 2001). Other studies have suggested that TN may also be higher under *Acacia* plantations because of high nitrogen concentrations in the litter and in root exudates

(Brockwell et al., 2005; Forrester et al., 2006). In contrast, Sang et al. (2013) found that TN concentrations in the top 10 cm were similar across plantation *A. mangium*, secondary forest and pasture in Vietnam. This author suggested that the observed lack of difference in soil properties between land uses could be explained by the short-term duration (4 – 7 years) of the plantations and pastures, and the fact that different soil types, including contrasting Ferric Acrisols and Xanthic Ferrasols, were examined in the study. Furthermore, the study only sampled the top 10 cm of the soil surface and the results from our study indicated that differences in soil properties may occur deeper into the soil profile.

The TC values measured for both land uses were consistent with values reported in previous studies in Vietnam (Table 5.4). In this study, TC concentration was higher by 2 – 10% under AH sites when compared with FSC sites to 30 cm depth. Previous studies in the tropics have found higher TC in *Acacia* plantations than in adjacent scrublands, open sites and grasslands (Kasongo et al., 2009; Yang et al., 2009; Wang et al., 2010; Anh et al., 2014; Dong et al., 2014). Higher soil C in *Acacia* plantations has been linked to the retention of all residues at harvest (Hardiyanto and Nambiar, 2014), the additional C by leached as dissolved organic C to the mineral soil during litter decomposition (Schulze, 2000) and the capacity for below-ground storage of C by tree roots (Gibbon et al., 2010). Tree roots have been observed to extend to a soil depth of 1.7 m in *Acacia* hybrid plantations (Hung et al; unpublished data). Litter deposition rates of 9.4 – 11.1 Mg ha^{-1} yr^{-1} for *A. mangium* plantations (Li et al., 2000; Hardiyanto and Wicaksono, 2008) and 4.8 – 66.7 Mg ha^{-1} yr^{-1} for *A. auriculiformis* plantations have been recorded (Li et al., 2000; Huong et al., 2008). Fast growing *Acacia* plantations show greater and more rapid litter deposition rates than adjacent scrubland, grassland

and abandoned land. Thus, the recovery of SOM in *Acacia* plantations is faster than those of other land uses.

The soil C/N ratio was significantly higher at all three depths under FSC sites compared to AH sites and may be explained by the loss of N from the system. Studies of fallow land after shifting cultivation of field rice, maize and cassava report decreased soil N levels in northwest Vietnam (Toan, 1990; Thuong, 2003). Inputs of more recalcitrant residues can increase the ratio of carbon to nitrogen and it is suggested that as decomposition rates decrease after cropping in FSC, soil C becomes increasingly recalcitrant (Kleber, 2010). The N-fixing capacity in AH sites means that higher N levels may develop relative to C levels. However a lower soil C/N ratio under *Acacia* compared to FSC cannot be necessarily assumed. Anh et al. (2014) showed that FSC had a comparable soil C/N ratio (17) to that of *A. mangium* land use.

Clay content in AH sites was slightly higher in FSC sites. This could be attributed to slope wash removing the clays in FSC sites. The practices of repeated surface soil cultivation (0 – 20 cm) and burning, particularly during cassava production, may facilitate surface water flow and associated soil erosion on the FSC sites (Sam, 1994; Rasul and Thapa, 2003; Anh et al., 2014). Nambiar and Harwood (2014) reported that in *Acacia* plantations similar intensive site disturbance and removal and/or burning of slash and litter at harvest will also result in the loss of soil structure, especially on sloping land with shallow soils. As observed in other tree systems, the tree crowns, roots and litter in AH may all help reduce soil erosion thus maintaining and even improving soil physical properties (Buresh and Tian, 1998; Tahir et al., 2009; Hiraoka and Onda, 2012). Although we attribute lower clay content in FSC sites to greater soil erosion as compared to the plantation sites, the differences in clay content were not marked. We cannot exclude the possibility that there were inherent differences in the soils on which the *Acacia* plantations had been established compared with soils under shifting cultivation.

In general, our study suggests that soil fertility (C and N) is lower under FSC sites than AH sites. Many of the reasons for this have been discussed above. Frequent shifting cultivation typically involves the use of repeated slash and burn and is associated with the removal of large amounts of plant residue and a reduction in SOM inputs (Tahir et al., 2009). In South Africa the burn and removal of litter and slash treaments on *E. grandis* resulted in the greatest loss of soil organic carbon (SOC) by the end of rotation, while the SOC content of residue-retained treatments was 8 – 10 g kg^{-1} higher than that of the burn and residue-removed treatments (du Toit et al., 2008). The lowest loss of N concentrations was observed with the retention of residue, compared to the burn and residue removal treatments (du Toit et al., 2008). The loss of dissolved TC and TN under slash and burn cultivation has shown to be dependent on the fire intensity and the quality/quantity of crop residues (Smith et al., 2005; Dovey and du Toit, 2012). Anh et al. (2014) studied the soil properties of nine different land uses in northern Vietnam and found that shifting cultivation with cassava was associated with one of the lowest soil fertility levels especially when compared to *Acacia* plantations. The authors attributed this low fertility to the type of crop, site preparation practices (slash and burn) and subsequent soil erosion and nutrient loss. Furthermore, under shifting cultivation in Vietnam, fallow periods (1 – 3 years) have become shorter compared to previous traditional systems, resulting in slower recovery of soil fertility (C and N) due to lower rates of litter production and a concomitant acceleration in erosion (Huon et al., 2013).

5.5. Conclusions

Total soil carbon and nitrogen concentrations were significantly higher while pH was significantly lower under *Acacia* hybrid plantations compared to neighbouring fallow-swidden land uses for 25 sites under acidic, degraded Acrisols in northern Vietnam. Our results also indicate that soil fertility of Acrisols is low, regardless of land use, which raises questions about the sustainability of both land uses. In particular, under AH sites, the low soil pH is a concern whereas under FSC sites, low TN and TC concentrations are potential problems and both need careful long term monitoring. This study also indicates that planting Acacia hybrid is a good option for the improvement of soil fertility and a possible strategy to offset C emissions. This study did not examine the influence of land use on soil properties over an extended period of time. *Acacia* plantations are widespread throughout the tropics and there is a need for long-term studies on the influence of land use and crop management on soil properties.

Acacia hybrid (AH) *v.s* adjacent fallow land within a shifting cultivation system (FSC).

Soil collection at Tuyen Quang.

CHAPTER 6

DISCUSSION, RECOMMENDATIONS AND CONCLUSIONS

CHAPTER 6. DISCUSSION, RECOMMENDATIONS AND CONCLUSIONS

6.1. Discussion

Fast-growing acacias are now the most important plantation forest species in Vietnam, in terms of both area planted and volume of wood production. Nearly half (46%) of the acacia plantation estate is managed by a large number of smallholders each with 1 – 2 hectares of plantation (Blyth and Hoang, 2013). The Vietnamese government's strategy for forestry targets both higher productivity and an increase in the production of sawlogs for local processing (MARD, 2015). In order to realise the potential value of forest sector, there remains a significant knowledge gap in the plantation sector about species selection, and profitable and sustainable silvicultural management practices. This thesis provides new information that forest managers can use to improve the management of *A.* hybrid plantations pulpwood and sawlogs. This chapter summarises the main findings and provides recommendations for future research to increase the productivity and quality of acacia plantations in Vietnam.

The 3-PG model (**Chapter 3**) was able to adequately predict *A.* hybrid growth during a full rotation for pulpwood production. The parameter values were developed for one experimental site and applied to 12 sites across Vietnam. A single set of parameters for 3-PG was able to estimate the growth and yield of *A.* hybrid plantations for a range of climates and soils. This study is the first to develop a method to estimate the *FR* used in 3-PG based on regressions of *FR* values obtained for each plot (independent variables) and the explanatory soil variables (dependent variables). The regressions showed the importance of basic cations Ca^{2+} and K^{+} as determinants of soil fertility, and the role that SOC may play in their mobilisation when cation levels are low. In addition, the study showed that growth differences between regions can be partially explained by the variations in soil characteristics as *FR* varied between sites. Thus the south had the highest fertility rating (*FR* = 0.7 – 0.8), it was average in north central (*FR* = 0.6) and lowest in the north and south central (*FR* = 0.3 – 0.5) regions.

The 3-PG model performed better at sites of average productivity in the north and north-central regions but over- and under-estimated *MAI* at sites of low and high productivity in the south-central and south. A potential reason may be differences in biomass partitioning of the different clones planted that can affect estimates of W_{stem}, *SV* and *LAI* (Almeida et al., 2004b). Uncertainties about soil depth and soil water holding capacity may also have affected model performance, and to reduce these uncertainties further field work is required (Almeida et al., 2004b; Landsberg and Sands, 2010). The modelling showed that monthly predictions of *ASW* were satisfactory although the measurements were concentrated at only one site and for limited period. The soil moisture measurements showed high variability during some of the months, but this was not detected by the model's monthly time-step suggesting that a daily time-step may be needed to improve model accuracy for predictions of *ASW* (Almeida and Sands, 2016). This variability in *ASW* may affect growth estimations, as has been similarly reported in other studies using the 3-PG model (Almeida et al., 2004b; Almeida et al., 2007). Almeida and Sands (2016) showed that using a daily water balance may improve the accuracy of the predictions; however it also demands more data on soil characteristics which is not necessarily available. Other potential sources of uncertainty were a lack of detailed information on soil depth and root distribution (Almeida et al., 2007; Landsberg and Sands, 2010; Almeida and Sands, 2016).

The most sensitive parameters affecting the prediction of stand volume were T_{opt}, Y and α_{Cx}. The parameters n_{S}, g_{Cx} and T_{opt} had a strong influence on biomass allocation, particularly on canopy production These findings mirror those from sensitivity analyses of 3-PG parameters for other species (Almeida et al., 2004b; Esprey et al., 2004; Xenakis et al., 2008; Song et al., 2013). The age of the plantation when the sensitivity analyses are carried out may impact on the results for at least some of these parameters demonstrated by running the sensitivity analysis for stands aged 7 and 15 years.

Many studies have demonstrated that forest growth is affected by water deficit (Dye, 2000; Almeida and Landsberg, 2003; Almeida et al., 2007). Water deficit occurring for a few months in all regions is likely to be the main factor limiting *Acacia* productivity across Vietnam. Comparisons of 3-PG predictions with observed stand properties (*DBH*, *BA*, *SV* and *MAI*) showed that growth in the south was higher than in north, north central and south central regions. These regional differences can be explained by the fact that water deficit during the dry season had a moderate effect on stand growth in the north, north central and south central regions (f_{ASW} <0.47), and less effect in the south (f_{ASW} >0.62). The intensity of the water deficit was associated with the length of the dry season which varied between 2 – 5 consecutive months with <40 mm monthly average rainfall.

Temperature and *VPD* also influenced *A.* hybrid growth, although less than rainfall. The mean monthly air temperature is approximately 6 °C lower in the north (22 °C) than to the south and central regions (28 °C) and growth rates were lower in winter at the northern sites. The effect of *VPD* on growth was similar to that of temperature in both the wet and dry seasons.

Analysis of the factors limiting productivity indicated how *A.* hybrid responds to differences and changes in environmental conditions. Such analyses could be applied to improve site-specific management such as the selection of drought tolerant clones matched to the risk of water deficit or temperature extremes in a particular region.

In **Chapter 4**, the response in stand *DBH* varied with thinning intensity and stand age. Early thinning from 1667 or 1111 to 600 or 450 trees ha^{-1} resulted in the highest percentage of trees in the larger *DBH* classes. There was lower *SV* in all thinned stands especially those thinned to 450 trees ha^{-1}. Lighter thinning from 2000 or 1667 to 1000 or 900 trees ha^{-1} resulted in lower diameter increments but higher yields of small sawlogs and total *SV*. Fertiliser application at thinning increased absolute growth responses of trees but the interaction with thinning was not clear. The absolute growth response to fertiliser is probably driven by low P levels in the soil. Lateritic low pH (3.4 – 4.4) soils strongly fix P and available P is only 1.8 – 4.9 mg kg^{-1}. Xu and Dell (2003) found that low pH and available P in soils are key factors that often result in an increase of eucalypt growth in response to P fertiliser application in China. It is possible that the small quantity of fertiliser applied per tree was not sufficient to lead to marked differences attributable to fertiliser × thinning interaction. Even though there was an apparent thinning intensity × fertiliser at higher thinning intensity this could also be explained by a reduction in water deficit with a reduced stocking rate as suggested by Huong (2016).

Medhurst et al. (2001) suggested that the selection of the final stand density should be such that the growth rate of individual trees during the rotation should be maximised as well as making the most of available site resources. It is clear that the thinning practices tested in this study across a wide range of different sites are suitable for producing sawlogs but that the precise thinning timing and intensity needs to match the site. **Chapter 4** showed that 3-PG can be used for modelling stand growth of *A.* hybrid plantations managed for saw logs with acceptable accuracy.

This model was able to produce long-term growth estimates, to examine the effects of different management practices and to estimate optimum rotation length. Modelling predictions suggested that *A.* hybrid plantations managed for large sawlog production would benefit growers by extending the rotation length to at least 5 – 7 years in the South and South Central Coast regions and to 6 – 10 years in the North, although longer rotations inevitably increase the risk of damage caused by typhoons. Thinning to 450 or 600 trees ha^{-1} were the best treatments to obtain the earliest harvest of larger sawlogs. The 3-PG parameters were adequate to predict growth and wood product responses to different thinning and fertiliser application. Cassidy et al. (2012) state that the benefit of thinning will depend on many factors associated with growing trees for sawlogs such as the costs of silvicultural operations including harvest, the effects of thinning on wood quality, final log sizes, the price of the product and its transport. The ability to model different future scenarios and associate these with cost benefit analyses is a significant advance towards ensuring that *A.* hybrid plantations grown for sawlogs in Vietnam are profitable.

In **Chapter 5**, the potential to improve soil fertility with second-rotation *Acacia* hybrid plantations at age 5 – 6 years was assessed on degraded gravelly and deeply weathered acid soils with low base saturation to 30 cm depth, and low activity clays with low to moderate natural fertility. The results showed that *A.* hybrid (AH) significantly increased soil SOC and soil N but lowered soil pH compared to neighbouring fallow shifting cultivation (FSC) land use in northern Vietnam. Other studies have shown that SOC in *Acacia* plantations were higher than in adjacent scrublands, open sites and grasslands in the tropics (Kasongo et al., 2009; Yang et al., 2009; Wang et al., 2010) though this increase was a function of management, the amount of litter and harvest residues, and the capacity for below-ground storage of C. In this study pH was up to >0.4 lower under AH than FSC land use. Cultivation by clearing the forest and burning leads to a decrease in SOC and N content in FSC land use (Smith et al., 2005).

6.2. Recommendations for further research

The study has provided new knowledge to enable sustainable and profitable silvicultural practices for *A.* hybrid. An important output is the calibration and application of 3-PG to modelling the productivity of *A.* hybrid at a wide range of sites and silvicultural regimes including thinning and fertilisation. This tool can now be further improved by data from the following activities:

- Maintenance and monitoring of existing experimental sites across Vietnam through to final harvest age (up to age 10 years) an annual destructive sample to give data for similar clones grown in the contrasting environments. This activity can be used to further refine the 3-PG model in terms of sawlog yield predictive capacity over a longer rotation. The trials can also be used at harvesting in a sawlog trial to evaluate sawlog quality and will allow a full economic analysis of different silvicultural treatments at different sites.

- New experimental trials to specifically investigate the rate of growth of thinned *Acacia* stands treated with fertiliser and the post-thinning consequences for growth.
- New experimental trials to monitor the effect of water deficits and thinning in *Acacia* stands.
- Characterisation of the highly variable soils in Vietnam that are planted with forest. Better understanding of soil texture, soil depth and root distribution will allow the more accurate prediction of soil water and fertility and therefore improve growth and biomass prediction.
- Data mining with input from new and existing trials to better quantify and understand the interactions between silvicultural practices (planting density, weed control, fertilisation, thinning and inter-rotational regimes) on the sustainability, productivity and profitability of *Acacia* forestry.
- This study was a test of whether, in the absence of adequate background information on the physiology and structure of the species, realistic simulations are possible using a parameter set that is based on a limited amount of field data and relies heavily on default Eucalyptus values for most of the species parameters. Obtaining data for model parameterisation is expensive and time-consuming. Some parameters can be obtained from the literature as these parameters have minimal variation between species. Further testing of these parameter values at physiologically significant times over the remainder of the

rotation is recommended to test model output and permit fine-tuning of parameters.

An improved 3-PG model can be used to:

- Assess the impact of climate variability (especially drought) and change on Vietnamese *Acacia* plantations across a wide range of ages and stand characteristics.
- Model potential productivity (taking into account nutrients extracted) to indicate nutrient requirements to sustain production over multiple rotations.

The combination of modelling and economic analyses of predicted sawlog *vs*. pulpwood yields may provide the information required by growers to minimise risk by targeting desired product recovery within the shortest possible rotation length. If rotations >10 years are required to grow sawlogs there are greater risks of damage from agents such as wind, storm, fire and pests. With such an approach inputs such as fertiliser and labour for thinning can be appropriately managed on a site basis to ensure both sustainability and profitability, increasing the incomes for growers.

6.3. Conclusions

This thesis has provided greater understanding of the impact of different silvicultural practices on the productivity and sustainability of *A*. hybrid plantations. For those investing in the establishment of *A*. hybrid plantations, this information can be used to assist the adoption of those practices that can maximise profit and the potential of sites for high-value timber production.

- ✓ The 3-PG model was successfully calibrated and validated to predict growth, yield and biomass production of *A.* hybrid plantations across a wide range of climates and soils in Vietnam.
- ✓ The model has provided valuable insights into environmental factors affecting the growth of *A.* hybrid plantations. Sensitivity analysis indicated how much the model parameters affect the main outputs and how this changes with stand age. This can help prioritise data collection and reduce costs of parameterisation, calibration and validation.
- ✓ The results showed that 3-PG can be used as an operational tool in *A.* hybrid management. The model accurately predicted the growth and yield responses to thinning and fertiliser regimes and estimated the length of rotations for sawlog production.
- ✓ Both early- and later-age thinning to 450 or 600 trees ha^{-1} led to the highest proportion of larger diameter logs within a 5 to 10 years rotation length. Alternatively, thinning to 900 or 1000 trees ha^{-1} also produce a thinning response and can provide considerable flexibility for management across a range of thinning prescriptions and site qualities if markets for thinned products exist.
- ✓ Fertilisation increased tree growth at sites with low fertility, especially at a density of 600 trees ha^{-1}. Therefore, the *SV* increment reduction caused by thinning would most probably be relieved if the thinning and fertilisation treatments are applied simultaneously.
- ✓ Compared with shifting land-use cultivation, *Acacia* hybrid plantations have positive effects on key soil properties, particularly in terms of soil C and N. The results showed that *A.* hybrid species was well-adapted to degraded Acrisols, high productivity being expressed in spite of low soil pH, indicating that

planting *A.* hybrid is a good option for improving soil fertility on steep sites and a possible strategy to offset C emissions.

REFERENCES

Adams, H.D., Williams, A.P., Xu, C., Rauscher, S.A., Jiang, X., McDowell, N.G., 2013. Empirical and process-based approaches to climate-induced forest mortality models. Frontiers in Plant Science 4, 438.

AGROINFO, 2014. Annual report 2013 of wood sector and prospect for 2014. Information Center for Agriculture and Rural Development.

Alemu, B., 2014. The role of forest and soil carbon sequestrations on climate change mitigation. Journal of Environment and Earth Science 4, 98–111.

Almeida, A.C., Landsberg, J.J., 2003. Evaluating methods of estimating global radiation and vapor pressure deficit using a dense network of automatic weather stations in coastal Brazil. Agricultural and Forest Meteorology 18, 237–250.

Almeida, A.C., Landsberg, J.J., Sands, P.J., Ambrogi, M.S., Fonseca, S., Barddal, S.M., Bertolucci, F.L., 2004a. Needs and opportunities for using a process-based productivity model as a practical tool in *Eucalyptus* plantations. Forest Ecology and Management 193, 167–177.

Almeida, A.C., Landsberg, J.J., Sands, P.J., 2004b. Parameterisation of 3-PG model for fast-growing *Eucalyptus grandis* plantations. Forest Ecology and Management 193, 179–195.

Almeida, A.C., Soares, J.V., Landsberg, J.J., Rezende, G.D., 2007. Growth and water balance of *Eucalyptus grandis* hybrids plantations in Brazil during a rotation for pulp production. Forest Ecology and Management 251, 10–21.

Almeida, A.C., Sands, P.I., Bruce, J., Siggins, A.W., Leriche, A., Battaglia, M., Batista, T.R., 2009. Use of a spatial process-based model to quantify forest plantation productivity and water use efficiency under climate change scenarios. 18 th World IMACS/MODSIM Congress, Cairns, 1618-1822.

Almeida, A.C., Siggins, A., Batista, T.R., Beadle, C., Fonseca, S., Loos, R., 2010a. Mapping the effect of spatial and temporal variation in climate and soils on *Eucalyptus* plantation production with 3-PG, a process-based growth model. Forest Ecology and Management 259, 1730–1740.

Almeida, A.C., Beadle, C., Paul, K., Siggins, A., 2010b. Methodology to Estimate the Effects of Climate Change on Vietnamese Forests. CSIRO Confidential Report to the World Bank, pp. 46.

Almeida, A.C., Anh, H.V., Beadle, C., Siggins, A., Paul, K., Sang, P.M., 2014. Modelling *Acacia mangium* production in Vietnam under current and future climates. Acacia 2014 "Sustaining the Future of Acacia Plantation Forestry" International Conference. IUFRO Working Party 2.08.07: Genetics and Silviculture of Acacia, Hue, Vietnam, 18–21 March 2014, Compendium of Abstracts, p. 113.

Almeida, A.C., Sands, P.J., 2016. Improving the ability of 3-PG to model the water balance of forest plantations in contrasting environments. Ecohydrology 9, 610–630.

Anderson, N.P., Hart, J.M., Sullivan, D.M., Christensen, N.W., Horneck, D.A., Pirelli, G.J., 2013. Applying Lime to Raise Soil pH for Crop Production (Western Oregon). Oregon State University Extension, pp. 21.

Anh, P.T.Q., Gomi, T., MacDonald, L.H., Mizugaki, S., Khoa, P.V., Furuichi, T., 2014. Linkages among land use, macronutrient levels, and soil erosion in northern Vietnam: A plot-scale study. Geoderma 232–234, 352–362.

Arisman, H., Hardiyanto, E.B., 2006. *Acacia mangium* - a historical perspective on its cultivation. In: Potter, K., Rimbawanto, A., Beadle, C. (Eds.), Proceedings of a workshop held in Yogyakarta, Indonesia, 7–9 February 2006. Canberra, ACIAR Proceedings No. 124, pp. 11–14.

Astera, M., 2010. Soil CEC explained understanding, measuring and using cation exchange capacity for nutritious crops. Acres USA 40, 25–28.

Aussenac, G., Granier, A., 1988. Effects of thinning on water stress and growth in Douglas-fir. Can. J. For. Res. 18: 100–105.

Barney, K., 2005. Central Plans and Global Exports: Tracking Vietnam's Forestry Commodity Chains and Export Links to China. Forest Trends, Washington D.C., United States, pp. 85.

Bationo, A.J., Kihara, B., Vanlauwe, B., Waswa, B., Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agricultural Systems 9, 13–25.

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science 47, 151–163.

Battaglia, M., Sands, P., 1998a. Application of sensitivity analysis to a model of *Eucalyptus globulus* plantation productivity. Ecological Modelling 111, 237–259.

Battaglia, M., Cherry, M.L., Beadle, C.L., Sands, P.J., Hingston, A., 1998. Prediction of leaf area index in eucalypt plantations: effects of water stress and temperature. Tree Physiology 18, 521–528.

Battaglia, M., Sands, P.J., 1998b. Process-based forest productivity models and their application in forest management. Forest Ecology and Management 102, 13–32.

Beadle, C., Barry, K., Hardiyanto, E., Irianto, R., Junarto, Mohammed, C., Rimbawanto, A., 2007. Effect of pruning *Acacia mangium* on growth, form and heart rot. Forest Ecology and Management 238, 261–267.

Beadle, C., Volker, P., Bird, T., Mohammed, C., Barry, K., Pinkard, L., Wiseman, D., Harwood, C., Washusen, R., Wardlaw, T., Nolan, G., 2008. Solid-wood production from temperate eucalypt plantations: a Tasmanian case study. Southern Forests 70, 45–57.

Beadle, C., Maria, O., Dung, P.T., Caroline, M., Huong, V.D., Dat, K.T., Daniel, M., Harwood, C., Morag, G., 2013a. Optimising Silvicultural Management and Productivity of High-Quality *Acacia* Plantations, especially for Sawlogs. Final Report: ACIAR Project FST/2006/087. Australian Centre for International Agricultural Research, Canberra, Australia, pp. 123.

Beadle, C., Trieu, D.T., Harwood, C.E., 2013b. Thinning increased saw-log values in fast growing plantations of *Acacia* hybrid in Vietnam. Journal of Tropical Forest Science 25, 42–51.

Beadle, C., Maria, O., Dung, P.T., Cao, T.T., Dat, K.T., Bon, P.V., Harwood, C., 2015. Extending silvicultural knowledge on sawlog production from *Acacia* plantations. Australian Centre for International Agricultural Research, Canberra, Australia, pp. 61.

Bernhard-Reversat, F., 1996. Nitrogen cycling in tree plantations grown on a poor sandy savanna soil in Congo. Applied Soil Ecology 4, 161–172.

Bin, H., Wuming, Q., Jun, D., Qingbiao, W., Feng, L., Yong, H., 2007. Function and value of water conservation in different age classes of *Acacia mangium* plantations. Frontiers of Forestry in China 2, 443–447.

Binh, N.N., Tuan, P.D., Thua, L.T., Quan, N.H., Apel, U., Vinh, N.H., Chuong, H., Thanh, N.T., Phong, D., 2004. Forest Plantation. Transportation Publisher, Hanoi, Vietnam, pp. 76 [in Vietnamese].

Binh, N.T., 2003. Yield Table of Monocultural *Acacia* hybird Plantations. Forestry University of Vietnam, Ha Noi, Vietnam, pp.53 [in Vietnamese].

Binkley, D., 1992. Ecology of mixtures of N_2-fixing and non-N_2-fixing tree species. In: Cannell, M.G.R., Malcolm, D.C., Robertson, P.A. (Eds.), Ecology of Mixed Species Stands. Blackwell Scientific Publications, Oxford, pp. 99–123.

Binkley, D., Giardina, C., 1997. Nitrogen fixation in tropical forest plantations. In: Nambiar, E.K.S., Brown, A.G. (Eds.), Management of soil, nutrients and water in tropical plantation forests. Australian Centre for International Agricultural Research Monograph 43, Canberra, pp. 297–337.

Binkley, D., 2005. How Nitrogen-Fixing Trees Change Soil Carbon. In: Binkley, D., Menyailo, O. (Eds.), Tree Species Effects on Soils: Implications for Global Change. Springer Netherlands, pp. 155–164.

Blyth, M.J., Hoang, L.S., 2013. Socio-economic factors influencing smallholder production of acacia sawlogs in Vietnam. Final Report Project FST/2007/025. Australian Centre for International Agricultural Research, ACIAR, GPO Box 1571, Canberra ACT 2601, Australia.

Bon, P.V., Harwood, C.E., 2016. Effects of stock plant age and fertiliser application at planting on growth and form of clonal *Acacia* hybrid. Journal of Tropical Forest Science 28, 187–194.

Booth, T.H., Jovanovic, T., Old, K.M., Dudzinski, M.J., 2000. Climatic mapping to identify high-risk areas for *Cylindrocladium quinqueseptatum* leaf blight on eucalypts in mainland South East Asia and around the world. Environmental Pollution 108, 365–372.

Booth, T.H., Hai, P.H., Hieu, N.K., Jovanovic, T., Landsberg, J., Parsons, M., 2001. Increasing carbon sequestration in planted forests in Vietnam through the use of genetically improved planting stock, and modelling to quantify the benefits achieved. Component 2: Carbon inventory and growth prediction. CSIRO Forestry and Forest Products Client Report for the International Greenhouse International Greenhouse Partnerships Office, Australian Department of Industry, Science and Resources, Canberra, Australia.

Bouillet, J.P., Laclau, J.P., Gonçalves, J.L.M., Moreira, M.R., Trivelin, P.C.O., Jourdan, C., Silva, E.V., Piccolo, M.C., Tsai, S.M., Galiana, A., 2008. Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil: 2. Nitrogen accumulation in the stands and biological N_2 fixation. Forest Ecology and Management 255, 3918–3930.

Bouwman, A.F., 1990. Soils and the Greenhouse Effect. John Wiley and Sons, Chichester, UK, pp. 575.

Brawner, J., Japarudin, Y., Lapammu, M., Rauf, R., Boden, D., Wingfield, M.J., 2015. Evaluating the inheritance of *Ceratocystis acaciivora* symptom expression in a diverse *Acacia mangium* breeding population. Southern Forests 77, 83–90.

Brockwell, J., Searle, S.D., Jeavons, A.C., Waayers, M., 2005. Nitrogen Fixation in Acacias: an Untapped Resource for Sustainable Plantations, Farm Forestry and Land Reclamation. Australian Centre for International Agricultural Research Monograph No. 115, Canberra, pp. 132.

Bryars, C., Maier, C., Zhao, D., Kane, M., Borders, B., Will, R., Teskey, R., 2013. Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. Forest Ecology and Management 298, 501–514.

Buresh, R.L., Tian, G., 1998. Soil improvement by trees in sub-Saharan Africa. Agroforestry Systems 38, 51–76.

Cassidy, M., Palmer, G., Glencross, K., Nichols, J.D., Smith, R.G.B., 2012. Stocking and intensity of thinning affect log size and value in *Eucalyptus pilularis*. Forest Ecology and Management 264, 220–227.

Cheng, B., Le Clue, S., 2010. Forestry in Asia. In: Carmody, L., Morales, R. (Eds.), Issues for Responsible Investors, Responsible Research Pte Ltd, Singapore, pp. 89.

Cheng, L., Leavitt, S.W., Kimball, B.A., Jr., P., P.J, Ottman, M.J., Matthias, A., Wall, G.W., Brooks, T., Williams, D.G., Thompson, T.L., 2007. Dynamics of labile and recalcitrant soil carbon pools in a sorghum free-air CO_2 enrichment (FACE) agroecosystem. Soil Biology and Biochemistry 39, 2250–2263.

Cole, T.G., Yost, R.S., Kablan, R., Olsen, T., 1996. Growth potential of twelve acacia species on acid soils in Hawaii. Forest Ecology and Management 80, 175–186.

Coops, N.C., Hember, R.A., Waring, R.H., 2010. Assessing the impact of current and projected climates on Douglas-Fir productivity in British Columbia, Canada, using a process-based model (3-PG). Canadian Journal of Forest Research 40, 511–524.

Craswell, E.T., Lefroy, R.D.B., 2001. The role and function of organic matter in tropical soils. Nutrient Cycling in Agroecosystems 61, 7–18.

CUCE, 2007. Cation Exchange Capacity (CEC). Agronomy Fact Sheet Series # 22. Department of Crop and Soil Sciences, College of Agriculture and Life Sciences, Cornell University. Cornell University Cooperative Extension (CUCE).

De Koninck, R., 1999. Deforestation in Vietnam. International Development Research Center, Ottawa, pp. 110.

Dell, B., Xu, D., Thu, P.Q., 2012. Managing threats to the health of tree plantations in Asia. In: Bandani, A.R., (Ed), New Perspectives in Plant Protection. InTech, Rijeka, Croatia, pp. 63–92.

Devi, N.L., Choudhury, B.U., 2013. Soil fertility status in relation to fallow cycles and landuse practices in shifting cultivated areas of Chandel district Manipur, India. IOSR Journal of Agriculture and Veterinary Science 4, 1–9.

Dias, L.E., Franco, A.A., Campello, E.F.C., 1994. Organic matter and nutrient dynamics in bauxite mined soil cultivated with *Eucalyptus pellita* and *Acacia mangium*. In: Balensiefer, M., de Araújo, A.J., Rosot, N.C. (Eds.), Simpósio Sul-americano I e Simpósio National II de Recupercdo de Áreas Degradadas. Fundacão de Pesquisas Florestais do Paraná, Curitiba, pp. 515–526.

Do, T.V., Lee, D.K., Thang, H.V., 2005. Rehabilitation of the native forest tree species in the forest plantations and denuded hills of Namlau commune, Sonla Province, Vietnam. Forest Science Technology 1, 51–58.

Do, T.V., Osawa, A., Thang, N.T., 2011. Recovery of vegetation structure and species diversity after shifting cultivation in northwestern Vietnam, with special reference to commercially valuable tree species. International Scholarly Research Network 2011, 1–12.

Dong, T.L., Doyle, R., Beadle, C., Corkrey, R., Quat, N.X., 2014. Impact of short-rotation *Acacia* hybrid plantations on soil properties of degraded lands in central Vietnam. Soil Research 52, 271–281.

Dovey, S.B., du Toit, B., 2006. A process based approach to nutritional sustainability in plantation forests: a literature review. Institute for Commercial Forestry Research

(ICFR) Bulletin Series No. 06/2012. Pietermaritzburg: Institute for Commercial Forestry Research, South Africa.

Dovey, S.B., du Toit, B., 2012. A process based approach to nutritional sustainability in plantation forests: a literature review. Institute for Commercial Forestry Research (ICFR) Bulletin Series No. 06/2012. Pietermaritzburg: Institute for Commercial Forestry Research, South Africa.

du Toit, B., Dovey, S.B., Smith, C.W., 2008. Effects of slash and site management treatments on soil properties, nutrition and growth of a *Eucalyptus grandis* plantation in South Africa. In: Nambiar, E.K.S. (Ed.), Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Piracicaba (Brazil) 22–26 November 2004 and Bogor (Indonesia) 6–9 November 2006. Bogor: Center for International Forestry Research, pp. 63–77.

Dung, P.T., Dat, K.T., Huong, V.D., Quang, L.T., Bon, P.V., 2013. Slash Management after Harvesting for Improving Soil Fertility and Growth Productivity of *Acacia auriculiformis* Plantations. Ministry of Agriculture and Rural Development, Hanoi, Vietnam [In Vietnamese].

Dye, P.J., 2000. Water-use efficiency in South African *Eucalyptus* plantations: a review. South Africa Journal of Science 189, 17–25.

Dye, P.J., Jacobs, S., Drew, D., 2004. Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa. Forest Ecology and Management 193, 197–218.

Esprey, L.J., Sands, P.J., Smith, C.W., 2004. Understanding 3-PG using a sensitivity analysis. Forest Ecology and Management 193, 235–250.

Eyles, A., Beadle, C., Barry, K., Francis, A., Glen, M., Mohammed, C., 2008. Management of fungal root-rot pathogens in tropical *Acacia mangium* plantations. Forest Pathology 38, 332–355.

FAO, 1982. Seed sources establishment and tree improvement project, Sabah, Malaysia. In: Pedley, L. (Ed.), Variation in *Acacia mangium* Willd. FAO/UNDP-MAL/78/009 Consultant's Report No. 8, Food and Agriculture Organization, Rome, pp. 41–42.

FAO, 2006. Guidelines for Soil Description. Food and Agriculture Organization, Rome.

FAO, 2015. Global Forest Resources Assessment 2015. FAO Forestry Paper No. 1. Food and Agriculture Organization, Rome.

Federici, S., Tubiello, F.N., Salvatore, M., Jacobs, H., Schmidhuber, J., 2015. New estimates of CO_2 forest emissions and removals: 1990–2015. Forest Ecology and Management 352, 89–98.

Folster, H., Khanna, P.K., 1997. Dynamics of Nutrient Supply in Plantation Soils. In: Nambiar, E.K.S., Brown, A.G. (Eds.), Management of Soil, Nutrients and Water in Tropical Plantation Forests. Australian Centre for International Agricultural Research (ACIAR), Canberra, pp. 339–378.

Fontes, L., Landsberg, J.J., Tomé, J., Tomé, M., Pacheco, C.A., Soares, P., Araujo, C., 2006. Calibration and testing of a generalized process-based model for use in Portuguese eucalyptus plantations. Canadian Journal of Forest Research 36, 3209–3221.

Forrester, D.I., Bauhus, J., Cowie, A.L., Vanclay, J.K., 2006. Mixed-species plantation of *Eucalyptus* with nitrogen-fixing trees: A review. Forest Ecology and Management 233, 211–230.

Forrester, D.I., Collopy, J.J., Beadle, C.L., Warren, C.R., Baker, T.G., 2012. Effect of thinning, pruning and nitrogen fertiliser application on transpiration, photosynthesis and water-use efficiency in a young *Eucalyptus nitens* plantation. Forest Ecology and Management 266, 286–300.

Forrester, D.I., Collopy, J.J., Beadle, C.L., Baker, T.G., 2013a. Effect of thinning, pruning and nitrogen fertiliser application on light interception and light-use efficiency in a young *Eucalyptus nitens* plantation. Forest Ecology and Management 288, 21–30.

Forrester, D.I., Elms, S.R., Baker, T.G., 2013b. Relative, but not absolute, thinning responses decline with increasing thinning age in a *Eucalyptus nitens* plantation. Australian Forestry 76, 121–127.

Forrester, D.I., Tang, X., 2016. Analysing the spatial and temporal dynamics of species interactions in mixed-species forests and the effects of stand density using the 3-PG model. Ecol. Model. 319: 233–254.

Franco, A.C., Lüttge, U., 2002. Midday depression in savanna trees:coordinated adjustments in photochemical, efficiency, photorespiration, CO_2 assimilation and water use efficiency. Oecologia 131, 356–365.

Garay, I., Pellens, R., Kindel, A., Barros, E., Franco, A.A., 2004. Evaluation of soil conditions in fast-growing plantations of *Eucalyptus grandis* and *Acacia mangium* in Brazil: a contribution to the study of sustainable land use. Applied Soil Ecology 27, 177–187.

Ghabbour, E.A., Davies, G. (Eds.), 2005. Humic Substances: Molecular Details and Applications in Land and Water Conservation. Taylor & Francis Inc, Washington, United States, pp. 268.

Gibbon, A., Silman, M.R., Malhi, Y., Fisher, J.B., Meir, P., Zimmermann, M., Dargie, G.C., Farfan, W.R., Garcia, K.C., 2010. Ecosystem carbon storage across the grassland–forest transition in the high Andes of Manu National Park, Peru. Ecosystems 13, 1079–1111.

Giller, K.E., 2001. Nitrogen Fixation in Tropical Cropping Systems. CABI Publishing, Wallingford, UK, pp. 297.

Glencross, K., Palmer, G., Pelletier, M.C., Nichols, J.D., Smith, R.G.B., 2011. Basal area increment is unaffected by thinning intensity in young *Eucalyptus dunnii* and *Corymbia variegata* plantations across different quality sites. Forest Ecology and Management 318, 326–333.

Gonçalves, J.L.M., Stape, J.L., Laclau, J.P., Bouillet, J.P., Ranger, J., 2008. Assessing the effects of early silvicultural management on long-term site productivity of fast-growing eucalypt plantations: the Brazilian experience. Southern Forests 70, 105–118.

Gonzalez-Benecke, C.A., Jokela, E.J., J.W.P., C., Bracho, R., Leduc, D.J., 2014. Parameterization of the 3-PG model for *Pinus elliottii* stands using alternative methods to estimate fertility rating, biomass partitioning and canopy closure. Forest Ecology and Management 327, 55–75.

González-García, M., Alimeida, A.C., Hevia, A., Majada, J., Beadle, C., 2016. Application of a process-based model for predicting the productivity of *Eucalyptus nitens* bioenergy plantations in Spain. GCB Bioenergy 8, 194–210.

Griffin, A.R., Midgley, S.J., Bush, D., Cunningham, P.J., Rinaudo, A.T., 2011. Global uses of Australian acacias - recent trends and future prospects. Diversity and Distribution 17, 837–847.

Hai, P.H., Jansson, G., Harwood, C.E., Hannrup, B., Thinh, H.H., 2008a. Genetic variation in growth, stem straightness and branch thickness in clonal trials of *Acacia auriculiformis* at three contrasting sites in Vietnam. Forest Ecology and Management 255, 156–167.

Hai, P.H., Harwood, C.E., Kha, L.D., Pinyopuarek, K., Thinh, H.H., 2008b. Genetic gain from breeding *Acacia auriculiformis* in Vietnam. Journal of Tropical Forest Science 20, 313–327.

Hardiyanto, E.B., 2006. Options for solid-wood products from *Acacia mangium* plantations. In: Potter, K., Rimbawanto, A., Beadle, C. (Eds.), Proceedings of a Workshop in Yogyakarta, Indonesia, 7–9 February 2006. Canberra, ACIAR Proceedings No. 124, pp. 87–92.

Hardiyanto, E.B., Wicaksono, A., 2008. Inter-rotation site management, stand growth and soil properties in *Acacia mangium* plantations in South Sumatra, Indonesia. In: Nambiar, E.K.S. (Ed.), Site Management and Productivity in Tropical Plantation Forests. Bogor: Center for International Forest Research (CIFOR), Proceedings of Workshops in Piracicaba (Bazil) 22–26 November 2004 and Bogor (Indonesia) 6–9 November 2006, pp. 107–122.

Hardiyanto, E.B., Nambiar, E.K.S., 2014. Productivity of successive rotations of *Acacia mangium* plantations in South Sumatra, Indonesia: impacts of harvest and inter-rotation site management. New Forests 4, 273–289.

Harwood, C.E., Williams, E.R., 1992. A review of provenance variation in growth of *Acacia mangium*. In: Carron, L.T., Aken, K.M. (Eds.), Breeding Technologies for Tropical Acacias. ACIAR Proceedings No. 37. Australian Centre for International Agricultural Research, Canberra, Australia, pp. 132.

Harwood, C.E., Kha, L.D., Thinh, H.H., Hai, P.H., 2007. Review of Acacia Genetic Resources and Propagation Methods to Support Sawlog Production in Vietnam. CARD Project Progress Report: 032/05VIE- Sustainable and Profitable Development of *Acacia* Plantations for Sawlog Production in Vietnam. Australian Centre for International Agricultural Research, Canberra, Australia, pp. 36.

Harwood, C.E., 2011. Strengthening the tropical acacia plantation value chain: the role of research. Journal of Tropical Forest Science 23, 1–3.

Harwood, C.E., Nambiar, E.K.S., 2014a. Sustainable plantation forestry in South-East Asia. ACIAR Technical Reports No. 84, Australian Centre for International Agricultural Research, Canberra, Australia, pp. 100.

Harwood, C.E., Nambiar, E.K.S., 2014b. Productivity of acacia and eucalypt plantations in Southeast Asia. 2. Trends and variations. International Forestry Review 16, 249–260.

Hazelton, P., Murphy, B., 2007. Interpreting Soil Test Results. What Do All the Numbers Mean? CSIRO Publishing, Melbourne, Australia, pp. 152.

Hidayati, N., Glen, M., Norrohmad, S.H., Rimbawanto, A., Mohammed, C., 2014. *Ganoderma steyaertanum* as a root rot pathogen of forest trees. Acacia 2014 "Sustaining the Future of Acacia Plantation Forestry" International Conference. IUFRO Working Party 2.08.07: Genetics and Silviculture of Acacia, Hue, Vietnam, 18–21 March 2014, Compendium of Abstracts.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal Climatology 25, 1965–1978.

Hiraoka, M., Onda, Y., 2012. Factors affecting the infiltration capacity in bamboo groves. Journal of Forest Research 17, 403–412.

Hua, L.Z., Morris, J., He, X.B., Jiang, X.D., 2007. Predicting *Eucalyptus* production in Southern China using the 3-PG model. Journal of Tropical Forest Science 19, 127–140.

Hung, T.D., 2014. NIR for Combined Selection in Hardwoods for both Growth and Wood Properties. PhD thesis. The University of Queensland, Australia, pp. 155.

Hung, T.T., Lee, D.K., Woo, S.Y., 2010. Growth of several indigenous species in the degraded forest in the northern Vietnam. International Journal of the Physical Sciences 5, 2664–2671.

Hung, T.T., Doyle, R., Eyles, A., Mohammed, C., 2016a. Comparison of soil properties under tropical *Acacia* hybrid plantation and shifting cultivation land use in northern Vietnam. Southern Forests 2016, 1–10.

Hung, T.T., Almeida, A.C., Eyles, A., Mohammed, C., 2016b. Predicting productivity of *Acacia* hybrid for a range of climates and soils in Vietnam. Forest Ecology and Management 367, 97–111.

Huon, S., de Rouw, A., Bonté, P., Robain, H., Valentin, C., Lefèvre, I., Girardin, C., Troquer, Y.L., Podwojewski, P., Sengtaheuanghoung, O., 2013. Long-term soil carbon loss and accumulation in a catchment following the conversion of forest to arable land in northern Laos. Agriculture, Ecosystems and Environment 169, 43–57.

Huong, V.D., Quang, L.T., Binh, N.T., Dung, P.T., 2008. Site management and productivity of *Acacia auriculiformis* plantations in South Vietnam. In: Nambiar, E.K.S. (Ed.), Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Piracicaba (Brazil) 22–26 November 2004 and Bogor (Indonesia) 6–9 November 2006. Bogor: Center for International Forestry Research, pp. 237.

Huong, V.D., Nambiar, E.K.S., Quang, L.T., Mendham, D.S., Dung, P.T., 2014. Improving productivity and sustainability of successive rotations of *Acacia auriculiformis* plantations in South Vietnam. Southern Forests, 1–8.

Huong, V.D., Mendham, D.S., Close, D.S., 2016. Growth and physiological responses to intensity and timing of thinning in short rotation tropical *Acacia* hybrid plantations in South Vietnam. Forest Ecology and Management 380, 232–241.

Huong, V.D., 2016. Understanding Growth and Physiological Responses to Slash Management, Thinning and Fertiliser Application in Short-Rotation Tropical Acacia Plantations. PhD Thesis. University of Tasmania, Australia, pp. 174.

Hurtt, G.C., Frolking, S., Fearon, M.G., Moore, B., Shevliakova, E., Malyshev, S., Pacala, S.W., Houghton, R.A., 2006. The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. Global Change Biology 12, 1208-1229.

Indufor, 2012. Strategic review on the future of forest plantations. Viewed 15 May 2016 from: http://ic.fsc.org/download.strategic-review-on-the-future-offorest-plantations-full-report.672.htm.

IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. In: Penman J., M. Gytarsky,T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe and F. Wagner (Eds), IPCC National Greenhouse Gas Inventories Programme. IPCC/OECD/IEA/IGES, Hayama, Japan.

IPCC, 2014. Climate change 2014. Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]. IPCC, Geneva, Switzerland, pp. 151.

Jean-Daniel, B., Olivier, B., 2014. Predictive approaches to forest site productivity: recent trends, challenges and future perspectives. Forestry 87, 109–128.

Jobbagy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications 10, 423–436.

Jürgensen, C., Kollert, W., Lebedys, A., 2014. Assessment of industrial roundwood production from planted forests. FAO Planted Forests and Trees Working Paper FP/48/E. Rome. Viewed 25 April 2016 from: http://www.fao.org/forestry/plantedforests/67508@170537/en/.

Kamo, K., Vacharangkura, T., Tiyanon, S., Viriyabuncha, C., Thaingam, R., Sakai, M., 2009. Response of unmanaged *Acacia mangium* plantations to delayed thinning in North-East Thailand. Journal of Tropical Forest Science 21, 223–234.

Kasongo, R.K., Van Ranst, E., Verdoodt, A., Kanyankagote, P., Baert, G., 2009. Impact of *Acacia auriculiformis* on the chemical fertility of sandy soils on the Batéké plateau, D.R. Congo. Soil Use and Management 25, 21–27.

Kha, L.D., 2001. Studies on the Use of Natural Hybrids between *A. mangium* and *A. auriculiformis* in Vietnam. Agriculture Publishing House, Hanoi, Vietnam, pp. 103 [in Vietnamese].

Kha, L.D., 2003. Selection, Breeding and Multiplication of Some Main Species for Afforestation in Vietnam. Agriculture Publishing House, Hanoi, Vietnam, pp. 292 [in Vietnamese].

Kha, L.D., Harwood, C.E., Kien, N.D., Baltunis, B.S., Hai, N.D., Thinh, H.H., 2012. Growth and wood basic density of acacia hybrid clones at three locations in Vietnam. New Forests 43, 13-29.

Kien, N.D., Thinh, H.H., Kha, L.D., Nghia, N.H., Hai, P.H., Hung, T.V., 2014. Acacia as a national resource of Vietnam. In, Acacia 2014 "Sustaining the Future of

Acacia Plantation Forestry" International Conference. IUFRO Working Party 2.08.07: Genetics and Silviculture of Acacia, Hue, Vietnam, 18-21 March 2014, Compendium of Abstracts.

Kim, N.T., Ochiishi, M., Matsumura, J., Oda, K., 2008. Variation in wood properties of six natural acacia hybrid clones in northern Vietnam. Journal of Wood Science 54, 436–442.

Kleber, M., 2010. What is recalcitrant soil organic matter? Environmental Chemistry 7, 320–332.

Korzukhin, M.D., Ter-Mikaelian, M.T., Wagner, R.G., 1996. Process versus empirical models: which approach for forest ecosystem management? Canadian Journal of Forest Research 26, 879–887.

Kunert, N., Schwendenmannand, L., Hölscher, D., 2010. Seasonal dynamics of tree sap flux and water use in nine species in Panamanian forest plantations. Agricultural and Forest Meteorology 150, 411–419.

Laclau, J.-P., Almeida, J.C.R., Gonçalves, J.L.M., Saint-André, L., Silveira, M.V., Ranger, J., Moreira, R.M., Nouvellon, Y., 2009. Influence of nitrogen and potassium fertilization on leaf lifespan and allocation of above-ground growth in *Eucalyptus* plantations. Tree Physiology 29, 111–124.

Lamb, D., Gilmour, D., 2003. Rehabilitation and Restoration of Degraded Forests. IUCN, Gland, Switzerland and Cambridge, UK and WWF, Gland, Switzerland, pp. 110.

Lamb, D., Erskine, P.D., Parrotta, J.A., 2005. Restoration of degraded tropical forest landscapes. Science 310, 1628–1632.

Lamb, D., 2011. Greening the Bare Hills: Tropical Forest Restoration in the Asia-Pacific Region, Springer Science, New York, pp. 579.

Landsberg, J.J., 1986. Physiological Ecology of Forest Production. Academic Press, Sydney, pp. 198.

Landsberg, J.J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95, 209–228.

Landsberg, J.J., Waring, R.H., Coops, N.C., 2001. The 3-PG forest model: matters arising from evaluation against plantation data from different countries. In: Carnus, J.-M., Dewar, R., Loustau, D., Tome, M., Orazio, C., (Eds.), Models for the Sustainable Management of Temperate Plantation Forests: Proceedings of the International Workshop, Bordeaux, France, 7–9 September 2000, pp. 31–43.

Landsberg, J.J., Waring, R.H., Coops, N.C., 2003. Performance of the forest productivity model 3- PG applied to a wide range of forest types. Forest Ecology and Management 172, 199–214.

Landsberg, J.J., Mäkelä, A., Sievänen, R., Kukkola, M., 2005. Analysis of biomass accumulation and stem size distributions over long periods in managed stands of *Pinus sylvestris* in Finland using the 3-PG model. Tree Physiology 25, 781–792.

Landsberg, J.J., Sands, P.J., 2010. Physiological ecology of forest production: Principles, Processes and Models. Academic Press, USA, pp. 331.

Lap, V.T., 1999. Natural Geography of Vietnam. Education Publishing House. Hanoi, Vietnam, pp. 78 [in Vietnamese].

Li, Z., Lin, Y., Peng, S.L., 2000. Nutrient content in litterfall and its translocation in plantation forests in south China. Chinese Journal of Applied Ecology 11, 321–326.

Li, Z., Peng, S.L., Rae, D., Zhou, G.-Y., 2001. Litter decomposition and nitrogen mineralisation of soils in subtropical plantation forests of Southern China, with special attention to comparisons between legumes and non-legumes. Plant and Soil 229, 105–116.

Loague, K., Green, R.E., 1991. Statistical and graphical methods for evaluating transport models: overview and application. Journal of Contaminant Hydrology 7, 51–73.

Luckai, N., Larocque, G.R., 2002. Challenges in the application of existing process-based models to predict the effect of climate change on C pools in forest ecosystems. Climate Change 55, 39–60.

Macedo, M.O., Resende, A.S., Garcia, P.C., Boddey, R.M., Jantalia, C.P., Urquiaga, S., Campello, E.F.C., Franco, A.C., 2008. Changes in soil C and N stocks and nutrient dynamics 13 years after recovery of degraded land using leguminous nitrogen-fixing trees. Forest Ecology and Management 255, 1516–1524.

Mäkelä, A., Landsberg, J.J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Ägren, G.I., Oliver, C.D., Puttonen, P., 2000. Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. Tree Physiology 20, 289–298.

Mäkinen, H., Hynynen, J., Isomäki, A., 2005. Intensive management of Scots pine stands in southern Finland: First empirical results and simulated further development. Forest Ecology and Management 215, 37–50.

MARD, 2001. Five Million Hectare Reforestation Program Partnership: Synthesis Report. Ministry of Agriculture and Rural Development, Hanoi, Vietnam, pp. 23–37 [in Vietnamese].

MARD, 2010. Vietnam Forestry Development Strategy 2006–2010. Ministry of Agriculture and Rural Development, Hanoi, Vietnam [in Vietnamese].

MARD, 2015. Approval for action strategy to improve productivity, quality and value of commercial plantation during period 2015–2020. Ministry of Agriculture and Rural Development, Hanoi, Vietnam.

McNamara, S., Tinh, D.V., Erskine, P.D., Lamb, D., Yates, D., Brown, S., 2006. Rehabilitating degraded forest land in central Vietnam with mixed native species plantings. Forest Ecology and Management 233, 358–365.

Medhurst, J.L., Beadle, C.L., 2001. Crown structure and leaf area index development in thinned and unthinned *Eucalyptus nitens* plantations. Tree Physiology 21, 989–999.

Medhurst, J.L., Beadle, C.L., Neilsen, W.A., 2001. Early-age and later-age thinning affects growth, dominance, and intraspecific competition in *Eucalyptus nitens* plantations. Canadian Journal of Forest Research 31, 187–197.

Medhurst, J.L., Battaglia, M., Beadle, C.L., 2002. Measured and predicted changes in tree and stand water use following high-intensity thinning of an 8-year-old *Eucalyptus nitens* plantation. Tree Physiology 22, 775-784.

Medhurst, J.L., Beadle, C.L., 2005. Photosynthetic capacity and foliar nitrogen distribution in *Eucalyptus nitens* is altered by high-intensity thinning. Tree Physiology 25, 981–991.

Medlyn, B.E., Duursma, R.A., Zeppel, M., 2011. Forest productivity under climate change: a checklist for evaluating model studies. Wiley Interdisciplinary Reviews: Climate Change 2, 332–355.

Meinzer, F.C., Jamesand, S.A., Goldstein, G., 2004. Dynamic of traspiration, sap lfow and use of stored water in tropical forest canopy trees. Tree Physiology 24, 901–909.

Meinzer, F.C., Bond, B.J., Warrenand, J.M., Woodruff, D.R., 2005. Dose water transport sacle univesally with tree size? Function Ecology 19, 558–565.

Mendham, D., Hardyanto, E., Sjarkowi, F., Nurudin, M., Soeprijadi, D., Wicaksono, A., Untung, S., White, D., Drake, P., Rimbawanto, A., 2010. Realising Genetic Gains in Indonesian and Australian Plantations through Water and Nutrient Management. Final Report: ACIAR Project FST/2004/058. Australian Centre for International Agricultural Research, Canberra, Australia, pp. 88.

Mendham, D., Rimbawanto, A., Mohammed, C., Glen, M., Hardie, M., Beadle, C., 2015. Increasing productivity and profitability of Indonesian smallholder plantations. Final Report: ACIAR Project FST/2009/051. Australian Centre for International Agricultural Research, Canberra, Australia, pp. 129.

Mendham, D.S., O'Connell, A.M., Grove, T.S., Rance, S.J., 2003. Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts. Forest Ecology and Management 181, 357–372.

Miller, R.E., Tarrant, R.F., 1983. Long-term growth response of Douglas-fir to ammonium nitrate fertilizers. Forest Science 29, 127–137.

Miura, S., Amacher, M., Hofer, T., San-Miguel-Ayanz, J., Ernawati, Thackway, R., 2015. Protective functions and ecosystem services of global forests in the past quarter-century. Forest Ecology and Management 352, 35–46.

Miyazawa, Y., Tateishi, M., Komatsu, H., Ma, V., Kajisa, T., Shokh, H., 2014. Tropical tree water use under seasonal waterlogging and drought in central Cambodia. Journal of Hydrobiology 515, 81–89.

Mohammed, C., Rimbawanto, A., Page, D.E., 2014. Management of basidiomycete root- and stem-rot diseases in oil palm, rubber and tropical hardwood plantation crops. Forest Pathology 44, 428-446.

Morris, J., Zhang, N.N., Yang, Z.J., Collopy, J., Xu, D.P., 2004. Water use by fast-growing *Eucalyptus urophylla* plantations in southern China. Tree Physiology 24, 1035-1044.

Nambiar, E.K.S., Harwood, C.E., 2014. Productivity of acacia and eucalypt plantations in Southeast Asia 1. Biophysical determinants of production: opportunities and challenges. International Forestry Review 16, 225–248.

Nambiar, E.K.S., Harwood, C.E., Kien, N.D., 2015. *Acacia* plantations in Vietnam: research and knowledge application to secure a sustainable future. Southern Forests: A Journal of Forest Science 77, 1–10.

Nambiar, E.K.S., Tiarks, A.E., Cossalter, C., Ranger, J. (Eds.), 2000. Site management and productivity in tropical plantation forests: a progress report. Center for International Forestry Research, Bogor, Indonesia, pp. 112.

Nghia, N.H., 1996. Climatic requirements of some of the main tree plantation species in Vietnam. In: Booth, T. (Ed.), Matching trees and sites ACIAR Proceedings No. 63, Australian Centre for International Agricultural Research, Canberra, pp. 43–49

Nghia, N.H., Kha, L.D., 1998. Selection of *Acacia* species and provenances for planting in Vietnam. In: Turnbull, J.W., Crompton, H.R., Pinyopusarerk, K. (Eds.), Recent Developments in Acacia Planting. ACIAR Proceedings No. 82. Australian Centre for International Agricultural Research, Canberra, pp. 130–135.

Nghia, N.H., 2003. Development of *Acacia* species in Vietnam. Agriculture Pulblishing House, Hanoi, Vietnam, pp. 67 [in Vietnamese].

Nghia, N.H., Chien, N.V., Thu, P.Q., 2010. Research to Select *Acacia* and *Eucalyptus* Clones for Disease Resistance and High-Yielding for Commercial Plantations. Ministerial Level Projects, Phase 2: 2006–2010. Scientific Report. Forest Science Institute of Vietnam, pp. 12 [in Vietnamese].

Nicholas, I., Gifford, H., 1995. Form Pruning Australian blackwood (*Acacia melanoxylon*)—NZ FRI experience. What's New in Forest Research No. 241. New Zealand Forest Research Institute, pp. 4.

Nightingale, J.M., Hill, M.T., Phinn, S.R., Davies, I.D., Held, A.A., Erskine, P.D., 2008a. Use of 3- PG and 3-PGS to simulate forest growth dynamics of Australian tropical rainforests - I. Parameterisation and calibration for old-growth, regenerating and plantation forests. Forest Ecology and Management 254, 107–121.

Nightingale, J.M., Hill, M.J., Phinn, S.R., Davies, I.D., Held, A.A., 2008b. Use of 3-PG and 3-PGS to simulate forest growth dynamics of Australian tropical rainforests - II. An integrated system for modelling forest growth and scenario assessment within the wet tropics bioregion. Forest Ecology and Management 254, 122–133.

Norisada, M., Hitsuma, G., Kuroda, K., Yamanoshita, T., Masumori, M., Tange, T., Yagi, H., Nuyim, T., Sasaki, S., Kojima, K., 2005. *Acacia mangium*, a nurse tree candidate for reforestation on degraded sandy soils in the Malay Peninsula. Forest Science 51, 498–510.

Nsalambi, V.N., Christopher, J.P., 2010. Effect of vegetation type on soil physical properties at Lincoln University Living Laboratory. Research Journal of Forestry 4, 1–13.

Old, K.M., Wingfield, M.J., Yuan, Z.Q., 2003. A Manual of Diseases of *Eucalypts* in South-East Asia. Center for International Forestry Research (CIFOR), Bogor, Indonesia, pp. 106.

Olesen, P.O., 1971. Water displacement method. A fast and accurate method to determine green volume of wood samples. Forest Tree Improvement 3, 1–23.

Paul, K.I., Polglase, P.J., Nyakuengama, J.G., Khanna, P.K., 2002. Change in soil carbon following afforestation. Forest Ecology and Management 168, 241–257.

Paul, K.I., Polglase, P.J., Richards, G.P., 2003. Predicted change in soil carbon following afforestation or reforestation, and analysis of controlling factors by linking a C accounting model (CAMFor) to models of forest growth (3PG), litter decomposition (GENDEC) and soil C turnover (RothC). Forest Ecology and Management 177, 485–501.

Paul, K.I., Booth, T.H., Jovanovic, T., Sands, P.J., Morris, J.D., 2007. Calibration of the forest growth model 3-PG to eucalypt plantations growing in low rainfall regions of Australia. Forest Ecology and Management 243, 237–247.

Payn, T., Carnus, J.M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, S., Orazio, C., Rodriguez, L., Silva, L.N., Wingfield, M.J., 2015. Changes in planted forests and future global implications. Forest Ecology and Management 352, 57–67.

Pérez-Cruzado, C., Muñoz Sáez, F., Basurco, F., Riesco, G., Rodríguez Soalleiro, R., 2011. Combining empirical models and the process based model 3-PG to predict *Eucalyptus nitens* plantation growth in Spain. Forest Ecology and Management 262, 1067–1077.

Phat, C.D., 2011. Report of the Five Million Hectares Reforestation Program and Plan for Forest Protection during period 2011–2020. Vietnamese Ministry of Agriculture and Rural Development, Hanoi, Vietnam [in Vietnamese].

Phuc, T.X., Nghi, T.H., Zagt, R., 2013. Forest Land Allocation in Viet Nam: Implementation Processes and Results. Infoormation Brief, May, 2013, Tropenbos International Viet Nam. Viewed 15 June 2016 from: http://www.tropenbos.org/publications/fo.

Phuong, V.T., 2007. The role of forests in environment protection. Journal of Agriculture and Rural Development, 4, 15–19 [in Vietnamese].

Phuong, V.T., 2011. Identify Carbon Stock and Analyse Economic Effects for *Pinus* Plantations to Meet CDM in Vietnam. Vietnamese Academy of Forest Science, Hanoi, Vietnam, pp. 169 [in Vietnamese].

Phuong, V.T., Anh, H.V., Lung, N.N., Sam, D.D., Ky, N.D., Lien, T.V., 2012. Forest Ecological Stratification in Vietnam. Techniques and Science Publishing House, Hanoi, Vietnam pp. 139 [in Vietnamese].

Pinkard, E.A., 2002. Effects of pattern and severity of pruning on growth and branch development of pre-canopy closure *Eucalyptus nitens*. Forest Ecology and Management 157, 217–230.

Que, N.D., Giang, D.T., Thang, N.V., 2010. Site Classification for Establishing Commercial Plantations of Some Major Tree Species in Different Ecological Regions in Vietnam. Agricultural Publishing House, HanNoi, Vietnam [in Vietnamese].

Quentin, A.G., O'Grady, A.P., Beadle, C.L., Worledge, D., Pinkard, E.A., 2011. Responses of transpiration and canopy conductance to partial defoliation of Eucalyptus globulus trees. Agricultural and Forest Meteorology 151, 356–364.

Rasul, G., Thapa, G.B., 2003. Shifting cultivation in the mountains of South and Southeast Asia: regional patterns and factors influencing the change. Land Degradation and Development 14, 495–508.

Rayment, G.E., Higgingson, F.R., 1992. Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press, Melbourne, Australia, pp. 330.

Rodríguez, R., Espinosa, M., Real, M., Inzunza, J., 2015. Analysis of productivity of radiata pine plantations under different silvicultural regimes using the 3- PG process-based model. Australian Forestry 65, 165–172.

Russel, A.E., Tauch, J.W., Valverde-Brrantesand, O.J., Fisher, R.F., 2007. Tree speceis effects on soil properties in experimental plantations in tropical moist forest. Soil Science Scociety of America Journal 71, 1389–1397.

Rutherford, D.W., Chiou, C.T., Eberl, D.D., 1997. Effects of exchanged cation on the microporosity of montmorillonite. Clays and Clay Minerals 45, 534–543.

Saha, D., Kukal, S.S., Sharma, S.D., 2011. Landuse impacts on SOC fractions and aggregate stability in typic ustochrepts of Northwest India. Plant and Soil 339, 457–470.

Sam, D.D., 1994. Shifting Cultivation in Vietnam: Its Social, Economic and Environmental Values Relative to Alternative Land Use. International Institute for Environment and Development, London, IIED Forestry and Land Use Series, No. 3, pp. 55.

Sam, D.D., 2001. Assessment of Potential Productivity of Forest Land in Vietnam. Statistics Publishing House, Hanoi, Vietnam [in Vietnamese].

Sam, D.D., Que, N.D., Siem, N.T., Binh, N.N., 2006. Forest Soils, Nutrition and Management. Transportation Publisher, Hanoi, Vietnam [in Vietnamese].

Sampson, D.A., Waring, R.H., Maier, C.A., Gough, C.M., Ducey, M.J., Johnsen, K.H., 2006. Fertilization effects on forest carbon storage and exchange, and net primary production: a new hybrid process model for stand management. Forest Ecology and Management 221, 91–109.

Sands, P.J., Landsberg, J.J., 2002. Parameterisation of 3-PG for plantation grown *Eucalyptus globulus*. Forest Ecology and Management 163, 273–292.

Sands, P.J., 2004. Adaptation of 3-PG to Novel Species : Guidelines for Data Collection and Parameter Assignment. Technical Report 141. Cooperative Research Centre (CRC) for Sustainable Production Forestry, Hobart, Australia, pp. 34.

Sang, P.M., 2008. Carbon Sequestration and Soil Fertility of Tropical Tree Plantations and Secondary Forests in Vietnam. PhD thesis. University of Queensland, Australia, pp. 140.

Sang, P.M., Lamb, D., Bonner, M., Schmidt, S., 2013. Carbon sequestration and soil fertility of tropical tree plantations and secondary forest established on degraded land. Plant and Soil 362, 187–200.

Sarshar, D., 2012. Hardwood Timber Supply & Demand in Asia: An Opportunity for Hardwood Plantation Investment. New Forests Asia (Singapore) Pte Ltd, Singapore, pp. 11.

Schiavo, J.A., Busato, J.G., Martins, M.A., Canellas, L.P., 2009. Recovery of degraded areas revegetated with *Acacia mangium* and *Eucalyptus* with special reference to organic matter humification. Scientia Agrícola 66, 353–360.

Schimel, D., Enting, I.G., Heimann, M., Tigley, T.M.L., Raynaud, D., Alves, D., Siegenthaler, U., 2000. CO_2 and the Carbon Cycle (Extracted from the Intergovernmental Panel on ClimateCchange (IPCC) Report, "Climate change, 1994"). In: Wigley, T.M.L., Schimel, D.S. (Eds.), The Carbon Cycle. Cambridge University Press, Cambridge, UK, pp. 7–37.

Schindelin, J., Arganda-Carreras, I., Frise, E., Kaynig, V., Longair, M., Pietzsch, T., Preibisch, S., Rueden, C., Saalfeld, S., Schmid, B., Tinevez, J.-Y., White, D.J., Hartenstein, V., Eliceiri, K., Tomancak, P., Cardona, A., 2012. Fiji: an open-source platform for biological-image analysis. Nature Methods 9, 676–682.

Schlesinger, W.H., Palmer, W.J., Megonigal, J.P., 2000. Soils and the Global Carbon Cycle. In: Wigley, T.M.L., Schimel, D.S. (Eds.), The Carbon Cycle. Cambridge University Press, Cambridge, UK, pp. 93–101.

Schulze, D. (Ed.), 2000. Carbon and Nitrogen in European Forest Systems. Springer, New York, pp. 498.

Sean, S., Jeffrey, A.S., 2015. Forest Resources Assessment of 2015 shows positive global trends but forest loss and degradation persist in poor tropical countries. Forest Ecology and Management 352, 134–145.

Sein, C.C., Mitlöhner, R., 2011. *Acacia* hybrid: Ecology and Silviculture in Vietnam. Center for International Forestry Research, Bogor, Indonesia, pp. 24.

Siregar, S.T.H., Nurwahyudi, Mulawarman, 2008. Effects of inter-rotation management on site productivity of *Acacia mangium* in Riau Province, Sumatra, Indonesia. In: Nambiar, E.K.S. (Ed), Site Management and Productivity in Tropical Plantation Forests: Proceedings of Workshops in Piracicaba (Brazil) 22-26 November 2004 and Bogor (Indonesia) 6-9 November 2006. Center for International Forestry Research, Bogor, Indonesia, pp. 93–106.

Smith, C.W., Little, K.M., Rolando, C.A., du Toit, B., 2005. A Framework for Monitoring and Measuring the Sustainability of Intensively Managed Southern African Forest Plantations. ICFR Bulletin Series No. 8/2005. Pietermaritzburg: Institute for Commercial Forestry Research, South Africa.

Smith, G., Brennan, P., 2006. First thinning in sub-tropical eucalypt plantations grown for high-value solid-wood products: a review. Australian Forestry 69, 305-312.

Smith, T.E., Osborne, D.O., Simpson, J.A., 2008. Inter-rotation management impacts on growth and soil properties in hybrid pine plantations on sandy soils in subtropical Australia. In: Nambiar, E.K.S. (Ed), Site Management and Productivity in

Tropical Plantation Forests. Proceedings of Workshops in Piracicaba (Brazil) 22-26 November 2004 and Bogor (Indonesia) 6-9 November 2006. Centre for International Forestry Research, Bogor, Indonesia, pp. 237.

Soares, P., Tomé, M., Skovsgaard, J.P., Vanclay, J.K., 1995. Evaluating a growth model for forest management using continuous forest inventory data. Forest Ecology and Management 71, 251–265.

Soil Survey Staff - NRCS, 2007. Official Soil Series Descriptions. Viewed 20 June 2016 from: http://soils.usda.gov/technical/classification/osd/index.html.

Soil Survey Staff, 2006. Keys to Soil Taxonomy (10th Edn.). United States Department of Agriculture, Natural Resources Conservation Service, Washington DC, USA, pp. 333.

Son, N.H., 2006. Reserach on Technology and Science Solutions to Develope Raw Wood Materials for Exporting. Final Report: Research Technology and Science in Forestry Period 2001–2005. Agriculture Publishing House, Hanoi, Vietnam, pp. 24–42 [in Vietnamese].

Song, X., Bryan, B.A., Almeida, A.C., Paul, K., Zhao, G., Ren, Y., 2013. Time-dependent sensitivity of a process-based ecological model. Forest Ecology and Management 256, 114–123.

Sprent, J.I., 1999. Nitrogen fixation and growth of non-crop legume species in diverse environments. Perspectives in Plant Ecology, Evolution and Systematics 2, 149–162. doi:10.1078/1433-8319-00068.

Srivastava, P.B.L., 1993. Silvicultural practices. In: Awang, K., Taylor, D. (Eds.), Heartrots in Plantation Hardwoods in Indonesia and Australia. Winrock International and FAO, Bangkok, pp. 113–147.

Stape, J.L., Ryan, M.G., Binkley, D., 2004. Testing the utility of the 3-PG model for growth of *Eucalyptus grandis* × *urophylla* with natural and manipulated supplies of water and nutrients. Forest Ecology and Management 193, 219–234.

Sumner, M.E. (Ed.), 1999. Handbook of Soil Science. CRC Press, Taylor & Francis, Boca Raton, FLorida, USA, pp. 2148.

Tahir, B.A.E., Ahmed, D.M., Ardo, J., Gaafar, A.M., Salih, A.A., 2009. Changes in soil properties following conversion of *Acacia senegal* plantation to other land management systems in North Kordofan State, Sudan. Journal of Arid Environments 73, 499–505.

Tarigan, M., Wingfield, M.J., van Wyk, M., Tjahjono, B., Roux, J., 2011. Pruning quality affects infection of *Acacia mangium* and *A. crassicarpa* by *Ceratocystis acaciivora* and *Lasiodiplodia theobromae*. Southern Forests 73, 187–191.

Thang, H.V., Thang, N.T., Quang, P.M., 2011. Growth of some acacia species planted in the silvicultural demonstration plantations of the "Forestry sector development Project" in Thua Thien Hue, Vietnam. Vietnam Journal of Forest Science 3, 1–6 [in Vietnamese].

Thompson, I.D., Okabe, K., Parrotta, J.A., Brockerhoff, E., Jactel, H., Forrester, D.I., Taki, H., 2014. Biodiversity and ecosystem services: lessons from nature to improve management of planted forests for REDD-plus. Biodiversity and Conservation 23, 2613–2635.

Thu, P.Q., Quynh, D.N., Dell, B., 2012. *Ceratocystis* sp. causes crown wilt of *Acacia* spp. planted in some ecological zones of Vietnam. In: Proceedings of International Conference on The Impacts of Climate Change to Forest Pests and Diseases in The Tropics, 8 - 10 October, Yogyakarta, Indonesia, pp. 38–44.

Thu, P.Q., Quynh, D.N., Fourle, A., Barnes, I., Wingfield, M., 2014. *Ceratocystis wilt* – a new and serious threat to *Acacia* plantations in Vietnam: taxonomy and pathogenicity. In: Acacia 2014 "Sustaining the Future of Acacia Plantation Forestry" International Conference, IUFRO Working Party 2.08.07: Genetics and Silviculture of Acacia, Hue, Vietnam, 18–21 March 2014, Compendium of Abstracts, p. 43.

Thuong, P.N., 2003. Study Characteristics on Process of Natural Regeneration and Proposed Silvicultural Practices for Reforestation after Shifting Cultivation in Thai Nguyen and Bac Kan provinces. PhD thesis. Forest Science Institute of Vietnam, Hanoi, Vietnam, pp. 162 [in Vietnamese].

Thuyet, D.V., 2010. Research on Intensive Afforestation Measures for Acacia, Eucalypt and Pine to Supply Timber. Final Report for MARD project. Vietnam Acacdemy of Forest Sciences, Hanoi, Vietnam, pp. 133 [in Vietnamese].

Tiarks, A., Nambiar, E.K.S., Cossalter, C., 1998. Site Management and Productivity in Tropical Forest Plantations. Occasional Paper No. 16. Center for International Forestry Research (CIFOR), Bogor, Indonesia, pp. 11.

Toan, B.T., 1990. Some Problems on Slash-and-burn Cultivation Soil in Northwestern Region of Vietnam and the Direction of Its Utilization. PhD thesis. Agriculture University, Hanoi, Vietnam, pp. 157.

Turnbull, J.W., Midgley, S.J., Cossalter, C., 1997. Tropical acacias planted in Asia: an overview. In: Turnbull, J.W., Crompton, H.R., Pinyopusarek (Eds.), Recent Developments in *Acacia* Planting. Proceedings of an International Workshop, 27–30 October 2007, Hanoi, Vietnam, Australian Centre for International Agriculture Research (ACIAR), Canberra, ACIAR Proceedings No. 82, pp. 130–135.

Valinger, E., Elfving, B., Mörling, T., 2000. Twelve-year growth response of Scots pine to thinning and nitrogen fertilisation. Forest Ecology and Management 134, 45–53.

van Bueren, M., 2005. *Acacia* hybrid in Vietnam. ACIAR Impact Assessment Series No. 27. Australian Centre for International Agricultural Research, Canberra, Australia, pp. 42. Viewed 24 May 2015 from: http://www.aciar.gov.au/web.nsf/doc/ACIA-65P4LP.

van Lierop, P., Lindquist, E., Sathyapala, S., Franceschini, G., 2015. Global forest area disturbance from fire, insect pests, diseases and severe weather events. Forest Ecology and Management 352, 78–88.

van Reewijk, L.P. (Ed.), 2002. Procedures for Soil Analysis (6th Edn.). Technical Paper No. 9, International Soil Reference and Information Centre, Wageningen, Netherlands, pp. 101.

Vance, E.D., Loehle, C., Wigley, T.B., Weatherford, P., 2014. Scientific Basis for Sustainable Management of *Eucalyptu*s and *Populus* as Short-Rotation Woody Crops in the U.S. Forests 5, 901–918.

Vanclay, J.K., 1998. Modelling Forest Growth and Yield - Application to Mixed Tropical Forests. CABI Publishing, Wallingford, UK, pp. 312.

Vega-Nieva, D.J., Tomé, M., Tomé, J., Fontes, L., Soares, P., Ortiz, L., Basurco, F., Rodrigez-Soallerio, R., 2014. Developing a general method for the estimation of the fertility rating parameter of the 3-PG model: application in *Eucalytus globus* plantations in northwestern Spain. Canadian Journal of Forest Research 43, 627–636.

Vien, T.D., Huong, P.T., Dung, P.T., 2001. Shifting Cultication in Vietnam. In: Vien, T.D. (Ed.), Indigenous Fallow Management in Vietnam. Agriculture Publishing House, Ha Noi, Vietnam, pp. 95–103 [in Vietnamese].

VNFOREST, 2014. Research on Developing Sawlog Plantations to Supply Restructure of Vietnamsese Forestry. Ministry of Agriculture and Rural Development (MARD), Hanoi, Vietnam [in Vietnamese].

Wang, F., Li, Z., Xia, H., Zou, B., Li, N., Liu, J., Zhu, W., 2010. Effects of nitrogen-fixing and non-nitrogen-fixing tree species on soil properties and nitrogen transformation during forest restoration in southern China. Soil Science and Plant Nutrition 56, 297–306.

Waugh, G., 1996. Properties of plantation grown eucalypts. In: Farm Forestry and Plantations: Investing in Future Wood Supply. Australian Forest Growers Conference, Mt. Gambier, Australia, pp. 83–93.

Wei, L., Marshall, J.D., Zhang, J., Zhou, H., Powers, R.F., 2014. 3-PG simulations of young ponderosa pine plantations under varied management intensity: Why do they grow so differently? Forest Ecology and Management 3213, 69–82.

West, P.W., 2014. Growing Plantation Forests. Springer International Publishing Switzerland, pp. 329.

Wezel, A., Steinmüller, N., Friedrichsen, J.R., 2002. Slope position effects on soil fertility and crop productivity and implications for soil conservation in upland northwest Vietnam. Agriculture Ecosystems and Environment 91, 113–126.

Wingfield, M.J., Roux, J., Wingfield, B.D., 2011. Insect pests and pathogens of Australian acacias grown as non-natives – an experiment in biogeography with far-reaching consequences. Diversity and Distributions 17, 968–977.

Woo, S.Y., Hung, T.T., Park, P.S., 2011. Stand structure and natural regeneration of degraded forestland in the northern mountainous region of Vietnam. Landscape and Ecological Engineering 7, 251–261.

Xenakis, G., Ray, D., Mencuccini, M., 2008. Sensitivity and uncertainty analysis from a coupled 3-PG and soil organic matter decomposition model. Ecological Modelling 219, 1–16.

Xu, D.P., Dell, B., 2002. Nutrient Management of Eucalypt Plantations in South China. In: Wei, R. and Xu, D. (Eds), *Eucalyptus* Plantation Research, Management and Development. World Scientific Publishing Co. Pte. Ltd., Singapore, pp. 269–288.

Yamashita, N., Ohta, S., Hardjono, A., 2008. Soil changes induced by *Acacia mangium* plantation establishment: comparison with secondary forest and *Imperata cylindrica* grassland soils in South Sumatra, Indonesia. Forest Ecology and Management 254, 362–370.

Yang, L., Liu, N., Ren, H., Wang, J., 2009. Facilitation by two exotic acacias: *Acacia auriculiformis* and *Acacia mangium* as nurse plants in South China. Forest Ecology and Management 257, 1786–1793.

Zhou, X., Peng, C., Dang, Q.-L., Chen, J., Parton, S., 2005. Predicting forest growth and yield in Northeastern Ontario using the process-based model of TRIPLEX 1.0. Canadian Journal of Forest Research 35, 2268–2280.